

# Constellation-X

# Spectroscopy X-Ray Telescope

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## Thermal and Mechanical Finite Element Analysis of Forming Mandrel and Slumping Glass

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# Objectives & Goals

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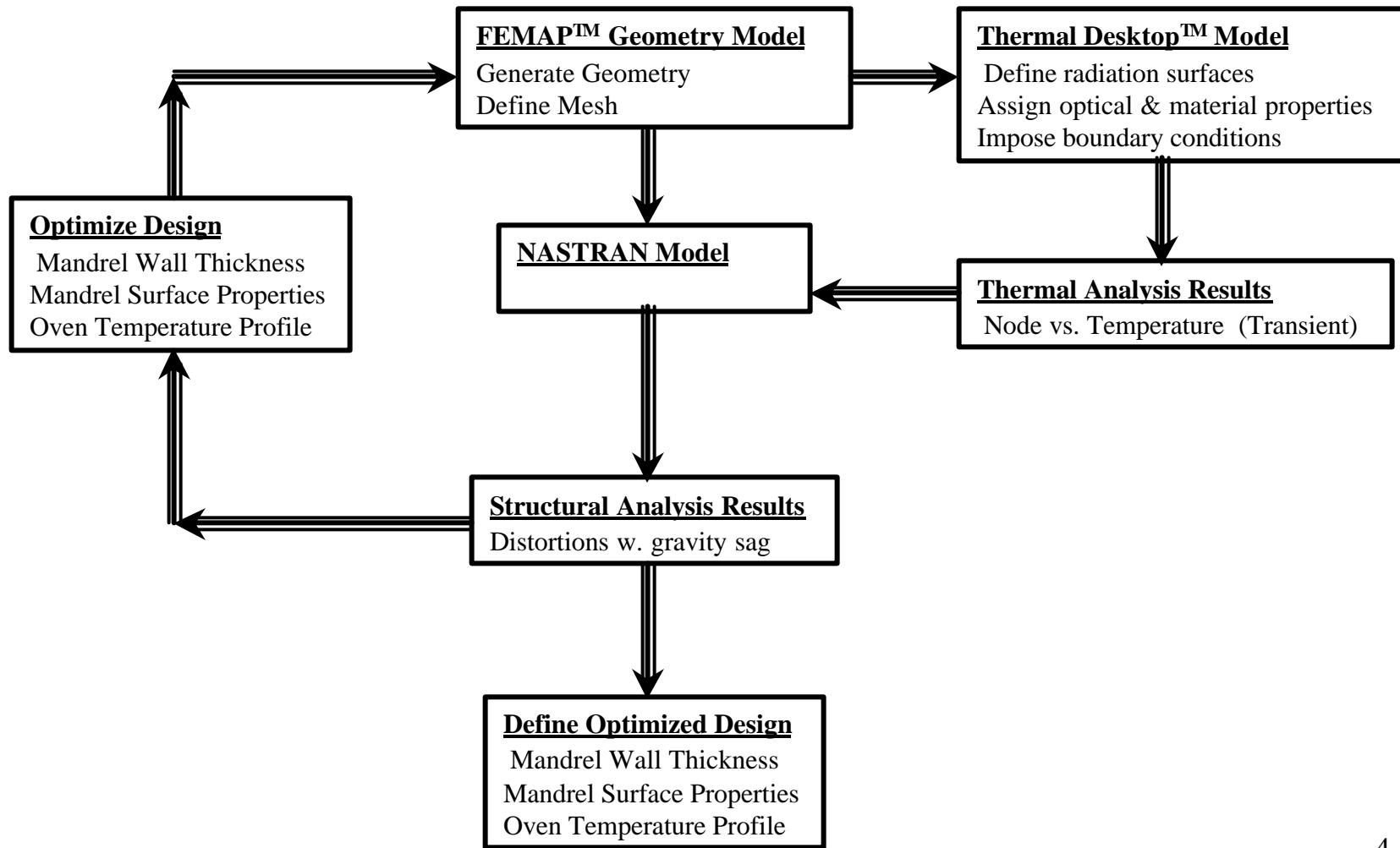
- Primary Objective
  - Identify optimum wall thickness for Constellation-X SRT mid-size forming mandrels.
- Secondary Goals
  - Identify and quantify mechanical and thermal parameters that cause mandrel and slumping glass temperature gradients that influence final glass surface figure.
  - Investigate methods to reduce slumping glass thermal/structural distortion resulting from the slumping process by performing analysis to optimize slumping process design.

# Executive Summary

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- Demonstrate Thermal/Structural Model information exchange
  - See thermal analysis process
- Develop thermal model of existing configuration
  - Stainless steel enclosure
  - Primary & Secondary mandrels
  - Slumping glass (flat & slumped configuration)
  - Mandrel support stand
- Perform thermal analysis parametric studies to optimize design
  - Mandrel surface coatings
  - Mandrel thickness
  - Oven temperature profile (specifically warm up times during slumping)

# Process



# Mandrel Wall Thickness

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- Strategy
  - Quantify mandrel gravity sag as function of wall thickness.
  - Incorporate thermal model to optimize wall thickness as a function of thermal gradient and gravity effects.
- Recommendation
  - 30mm wall thickness is recommended
    - Temperature gradients are reduced with reduction in mandrel thickness
    - Reduction limited to 30mm due to structural effects

# Mandrel Surface Coatings

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- Strategy
  - Perform parametric studies to determine optimum coating combination for mandrel surfaces that produces minimum mandrel temperature gradients
- Recommendation
  - Inside surface:            High **e** coating as practical
  - Outside surface:        High **e** coating as practical
  - Ends:                      Low **e** coating; Platinum

# Oven Warm Up Temperature Profile

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- Strategy
  - Perform parametric studies to determine optimum temperature warm up time during the slumping process
- Recommendation
  - In general, longer warm up time is better within reason
  - At least 6-8 hour warm up time for period when slumping glass temperature increases from 520°C to 620°C

# Future Work

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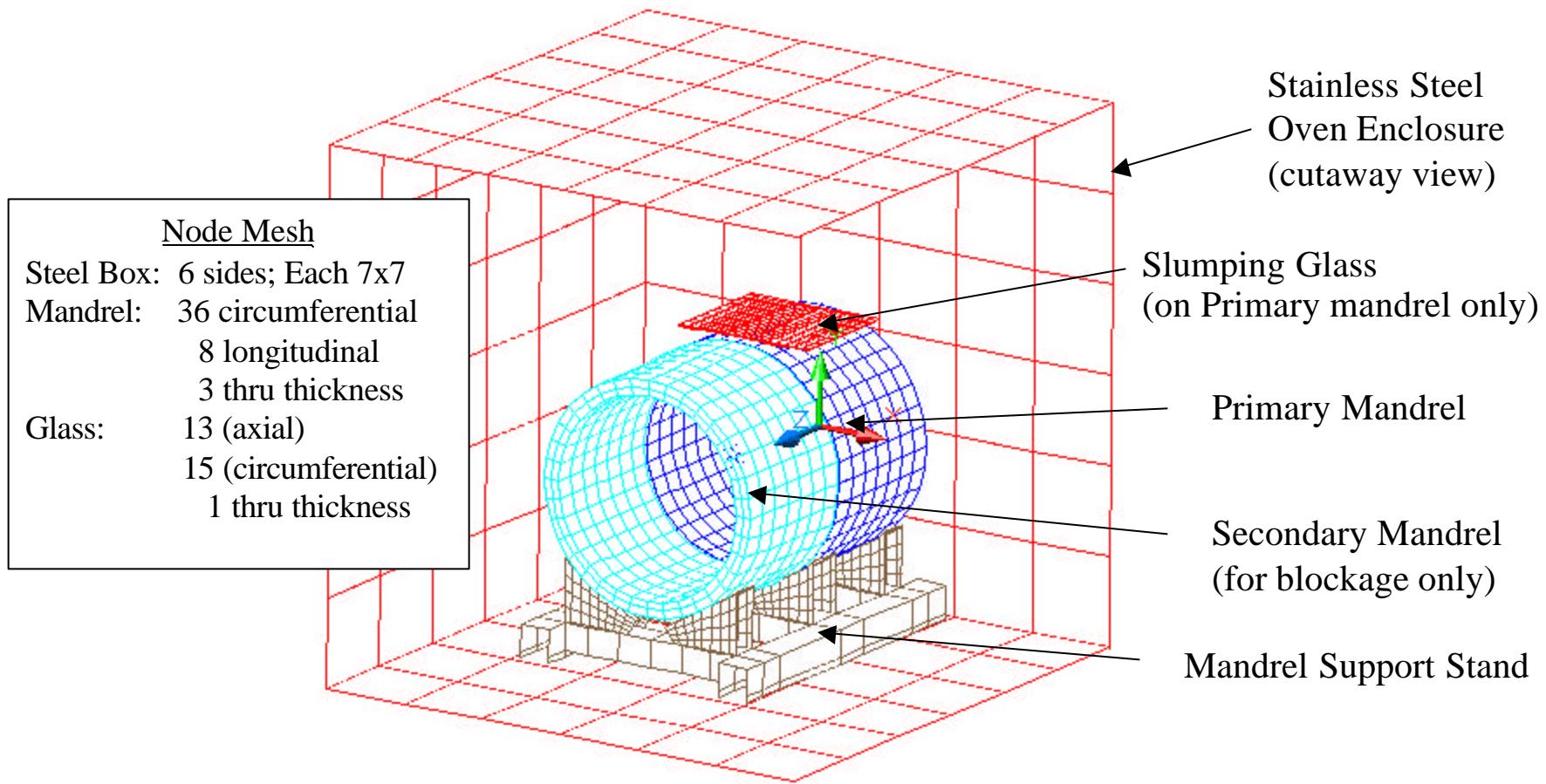
- Analysis to Optimize Design
  - Model outside steel enclosure
  - Slumping glass coatings ??
  - Heater rod thru mandrel center
  - Slab mandrel configuration
  - Different mandrel materials
- Test & Observation to Characterize Oven Performance
  - Instrumentation to measure temperature profile
    - Mandrel
    - Slumping Glass
    - Steel Enclosure
  - Window to observe slumping

# **Attachment A**

## **Forming Mandrels Thermal Analysis**

# Thermal / Structural Model

## Geometric Configuration



# Assumptions

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- Boundary conditions
  - Imposed on steel box enclosure (oven outside steel box not modeled)
  - Stainless steel enclosure temperature profile (see plot)
  - Assume  $\Delta T = 15^\circ\text{C}$  from box top/sides to bottom
- Neglect convection
- Material Properties
  - $k, mC_p = f(T)$
  - $r = \text{constant}$
- Optical properties

Sample	TMM Model $\epsilon$
Pristine Steel Fixture <sup>1</sup>	0.20
Baked Steel Fixture <sup>1</sup>	0.49
Slumping Glass <sup>1,2</sup>	0.61
Generic Black	0.90
<b>Mandrel</b>	
Uncoated Surface <sup>1</sup>	0.50
Platinum w. BN Coat <sup>1,3</sup>	0.14
Platinum	0.08

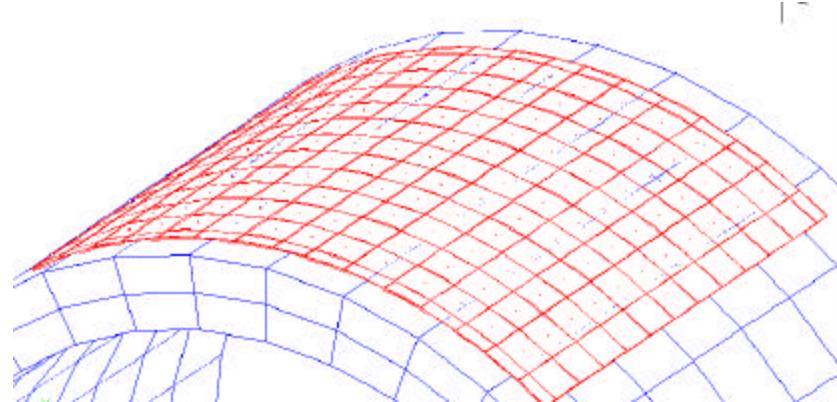
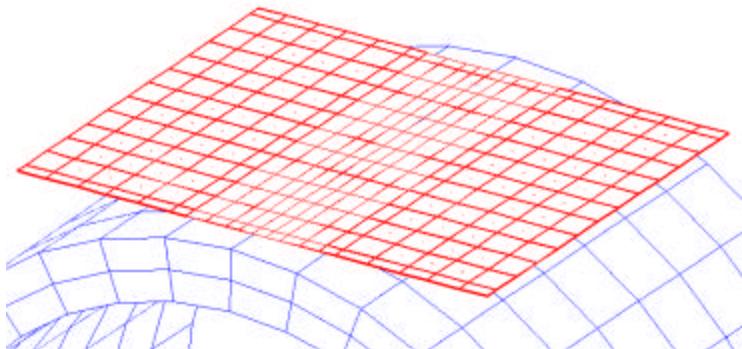
NOTES: 1) measurement @22°C; value adjusted for 580°C

2) transmittance = 0.33

3) measured data ranges from 0.14 to 0.30  
conservative to use 0.14

# Assumptions (*continued*)

## Slumping Glass Interface Conductance



Flat Configuration <i>warm up T&lt;580° C</i>	Interface Conductance	
	(BTU/hr/ft <sup>2</sup> /°F)	(W/mm <sup>2</sup> /°C)
center to 13mm (0-3°) <sup>1</sup>	30	1.70E-04
13 to 17mm (3-4°) <sup>2</sup>	23	1.31E-04
17 to 43mm (4-10°) <sup>2</sup>	7	3.97E-05
43-152mm (>10°) <sup>3</sup>	0	0.00E+00

Slumped Configuration <i>warm up T&gt;580° C; soak; cool down</i>	Interface Conductance	
	(BTU/hr/ft <sup>2</sup> /°F)	(W/mm <sup>2</sup> /°C)
constant over surface <sup>1</sup>	10	5.68E-05

- Notes:
- 1) surface to surface contact conductance per area due to gravity
  - 2) conduction through air gap at smaller distances integrated over mandrel curvature
  - 3) conduction through air gap at larger distances calculated to be negligible

# Parametric study of factors that affect mandrel & slumping glass temperature uniformity

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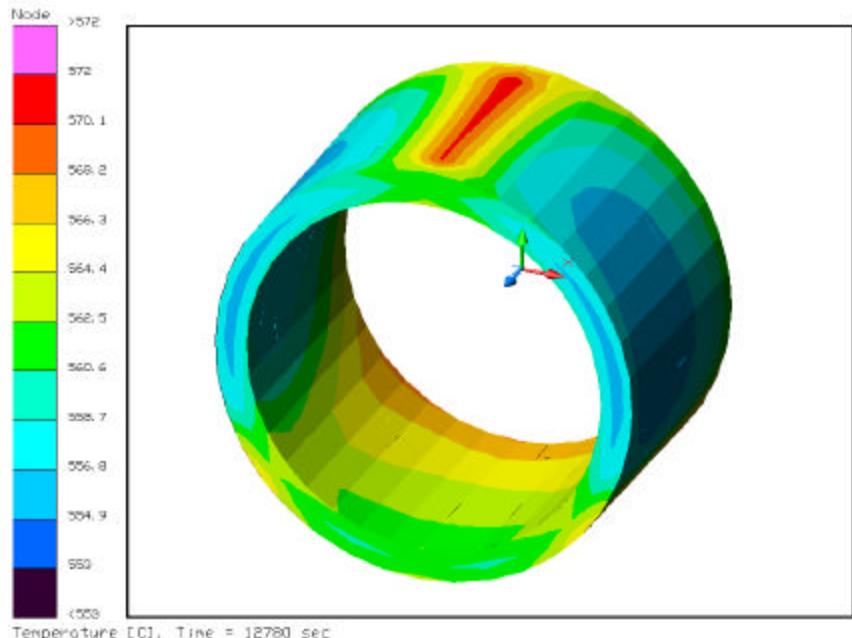
- Analysis performed for Primary Mandrel & Slumping Glass
  - Overall objective to reduce slumping glass & mandrel temperature gradients
- Secondary Mandrel for blockage only
- Results from analysis
  - Color contour snapshots at critical times during warm up & cool down
    - To show overall thermal response
  - Mandrel & slumping glass: Time vs. Temperature plots
    - To show thermal response (temperature lag relative to oven)
  - Mandrel: Time vs. Delta Temperature (axial, radial, circumferential)
    - To indicate mandrel degree of distortion
  - Slumping glass: Time vs. Delta Temperature (axial, circumferential)
    - To indicate magnitude of warping and location where slumping starts
- Parametric Studies
  - Mandrel thickness: 20mm vs. 30mm vs. 40mm
  - Mandrel end surfaces: uncoated vs. Platinum
  - Mandrel outside surface: Pt + BN; 240° vs. 360° coverage
    - Pt + BN ( $\epsilon = 0.14$ ) vs. black ( $\epsilon = 0.9$ )
  - Mandrel inside surface: uncoated ( $\epsilon = 0.5$ ) vs. black ( $\epsilon = 0.9$ )
  - 520°C to 620°C warm up time: 4 hrs vs. 8 hrs

# Results

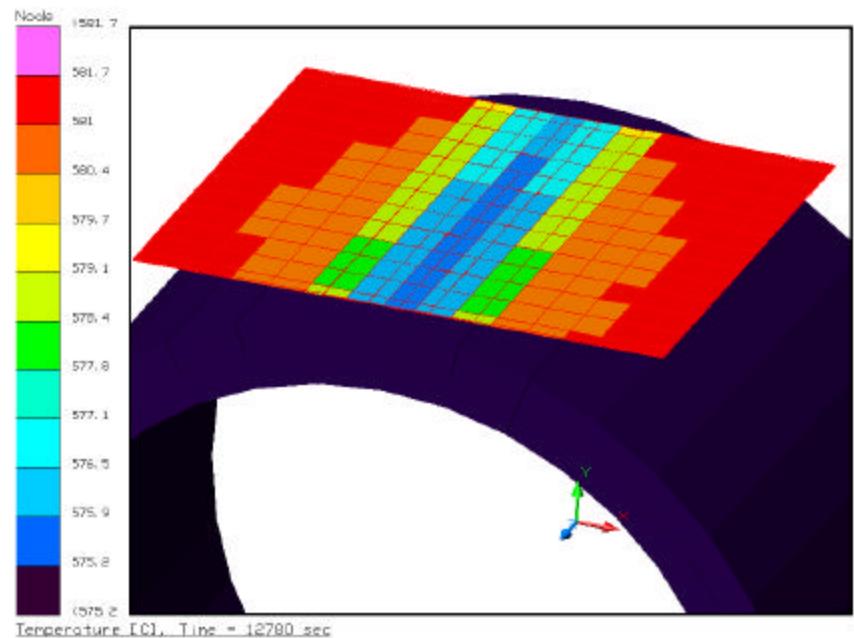
## Mandrel Properties

top 240° Pt/BN  
bottom 120° uncoated  
ends Pt  
inside uncoated

**Warm Up;  $T_{glass} = 575^{\circ}\text{C}$**



**Primary Mandrel (glass not shown)**



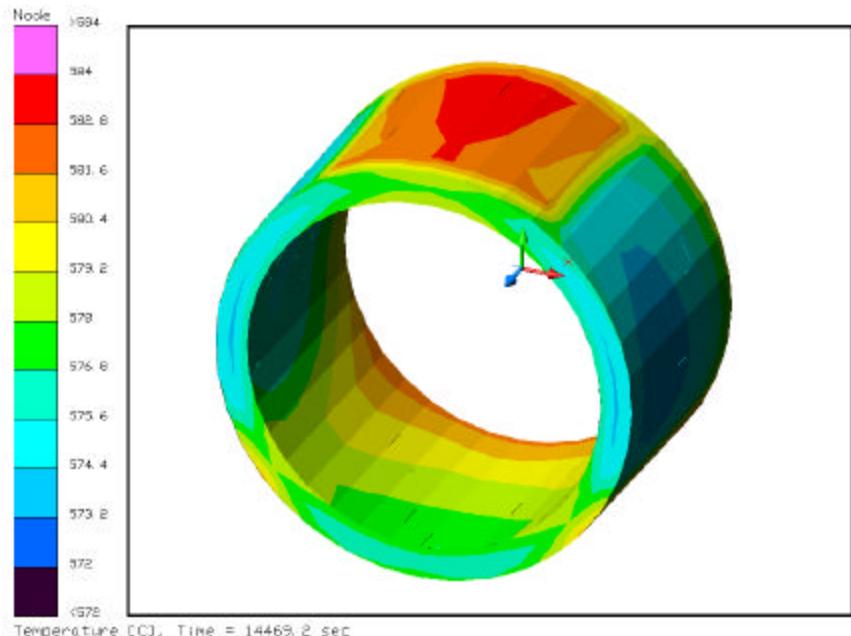
**Slumping Glass**

# Results

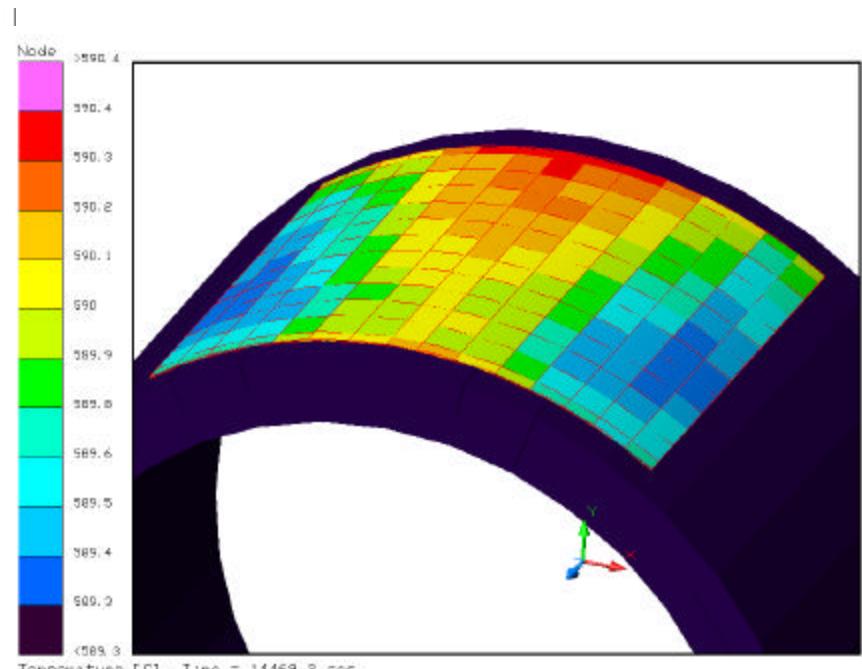
## Mandrel Properties

top 240° Pt/BN  
bottom 120° uncoated  
ends Pt  
inside uncoated

**Warm Up;  $T_{glass} = 590^{\circ}\text{C}$**



**Primary Mandrel (glass not shown)**



# Results

## Mandrel Properties

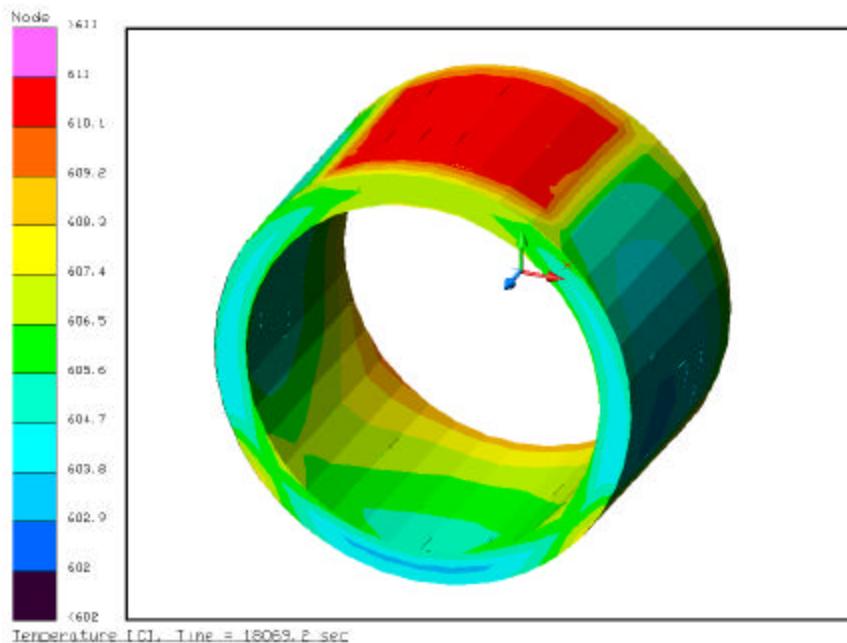
top 240° Pt/BN

bottom 120° uncoated

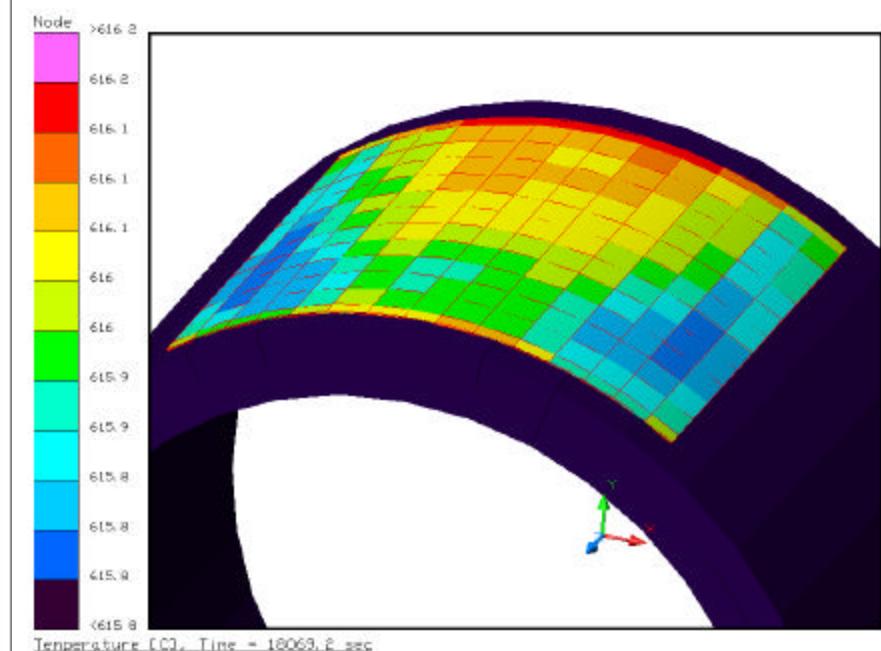
ends Pt

inside uncoated

**Begin Soak;  $T_{glass} = 615^{\circ}\text{C}$**



Primary Mandrel (glass not shown)



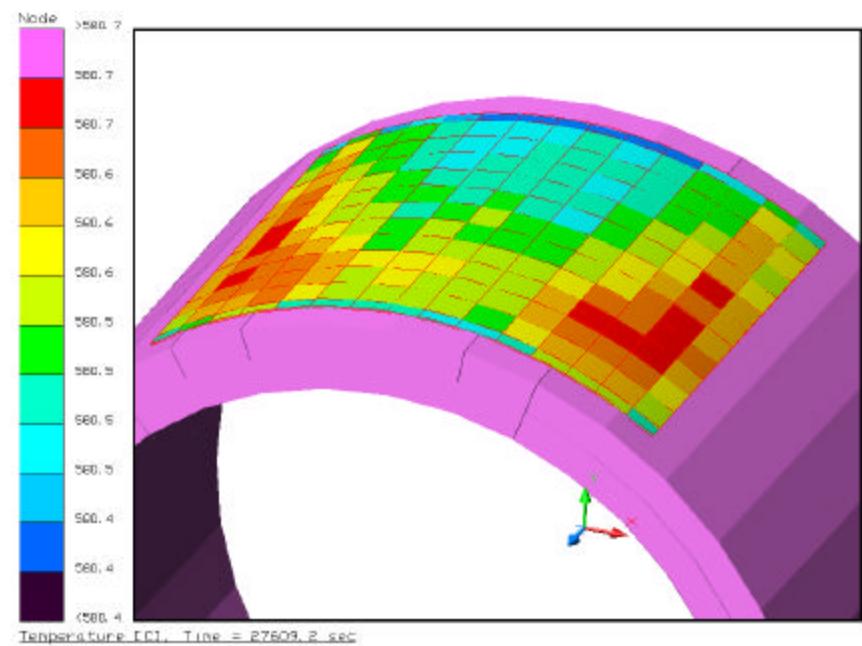
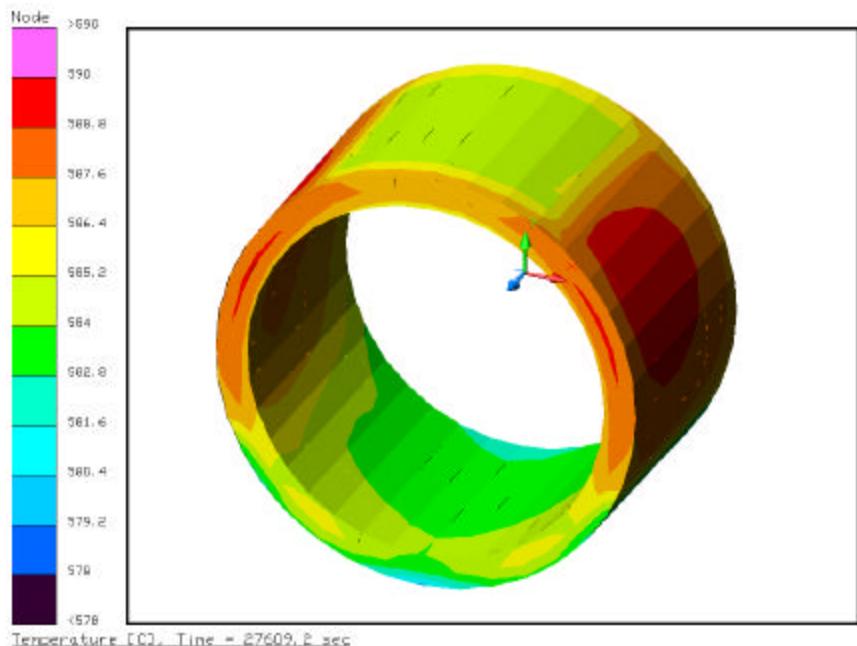
Slumping Glass

# Results

## Mandrel Properties

top 240° Pt/BN  
 bottom 120° uncoated  
 ends Pt  
 inside uncoated

Cool Down;  $T_{glass} = 580^{\circ}\text{C}$

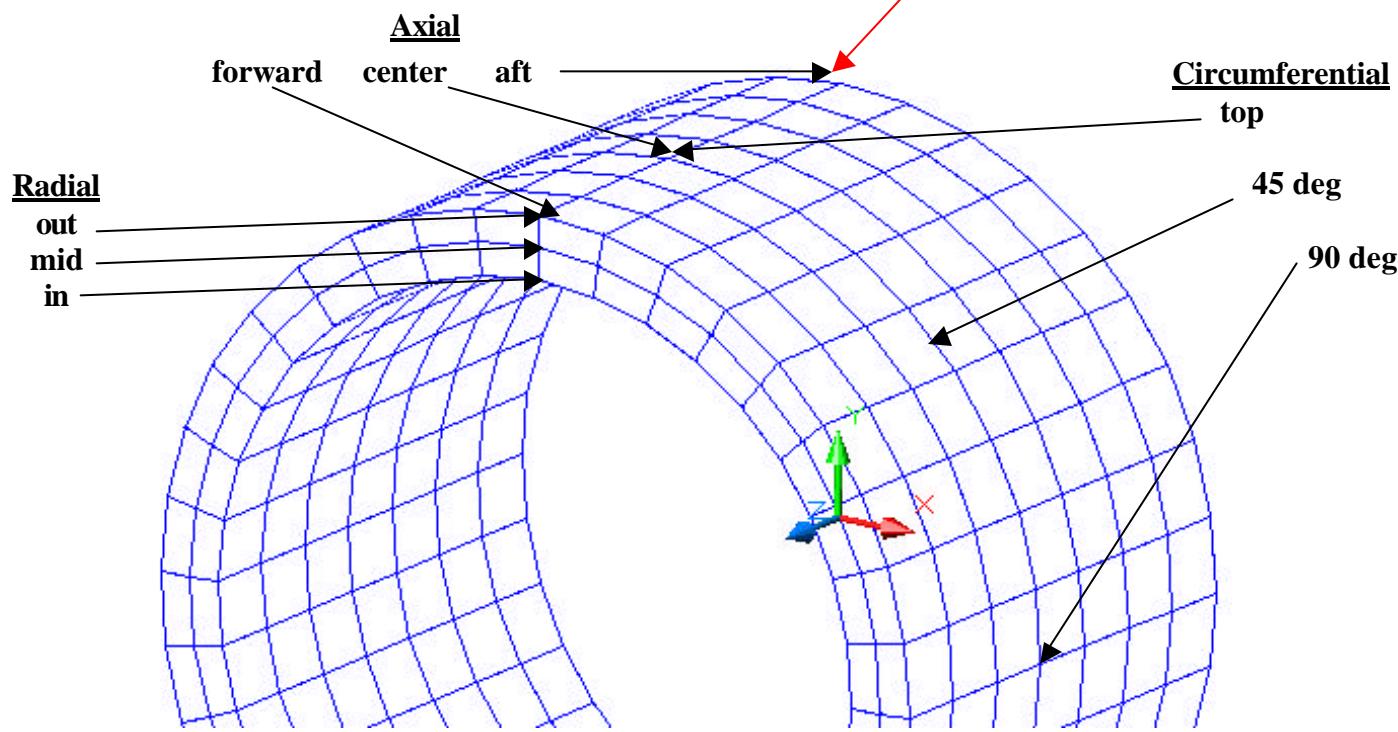


# Mandrel Node Location Definitions

## Format

[axial] [radial] [circumferential]

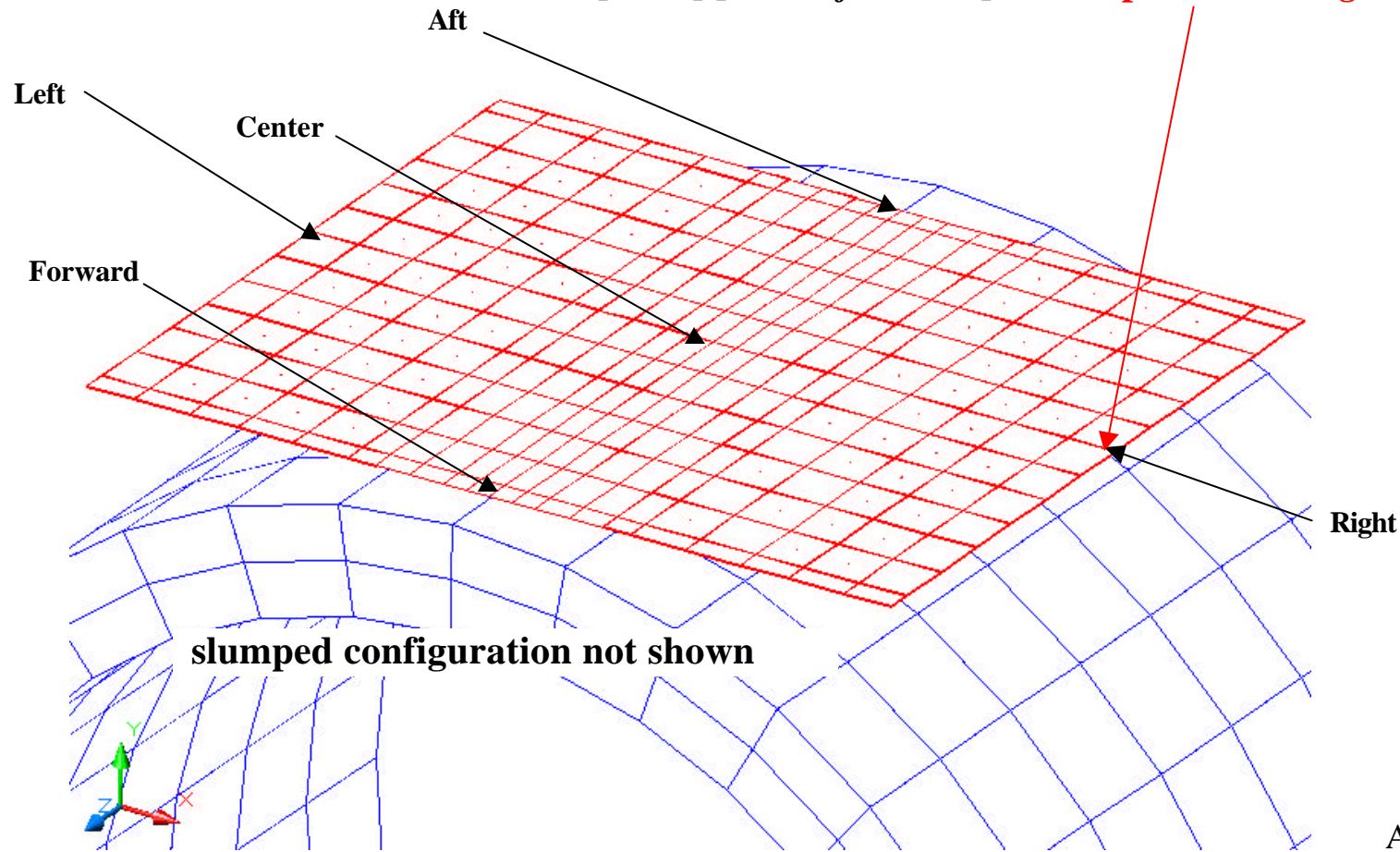
**Example:** *aft out top*



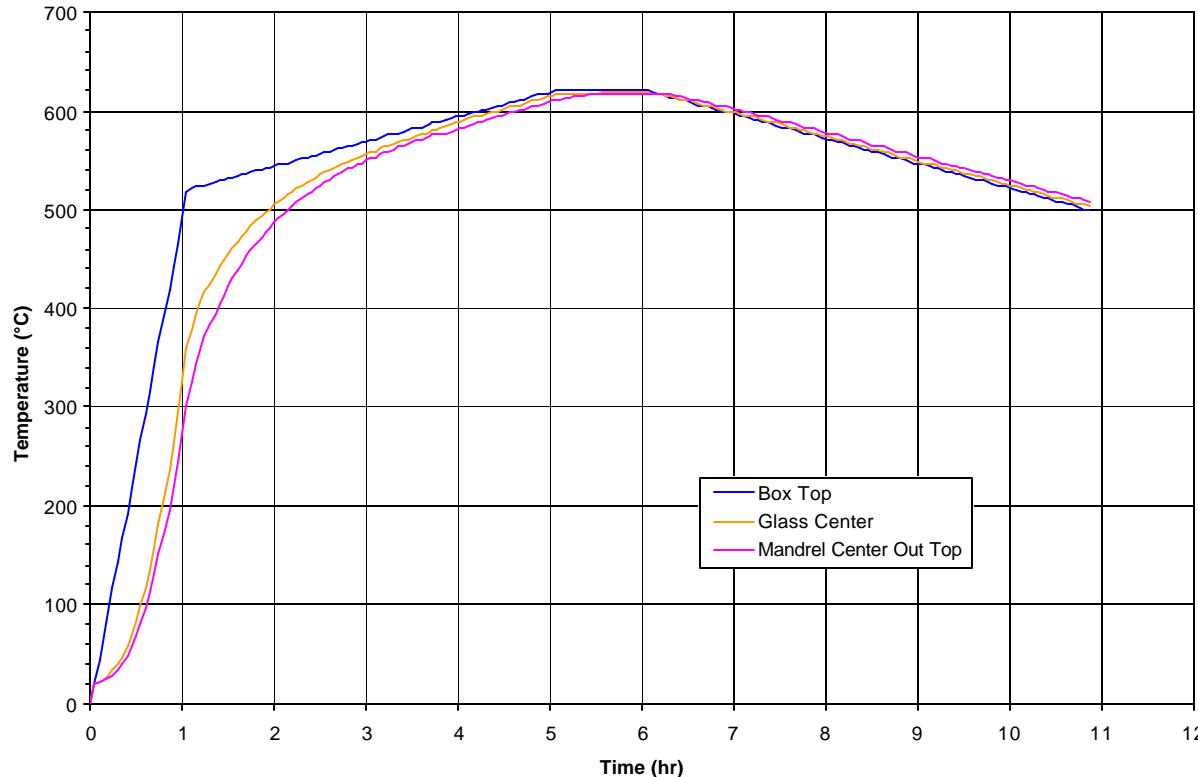
# Slumping Glass Node Location Definitions

## Format

[axial] [circumferential] **Example: center right**

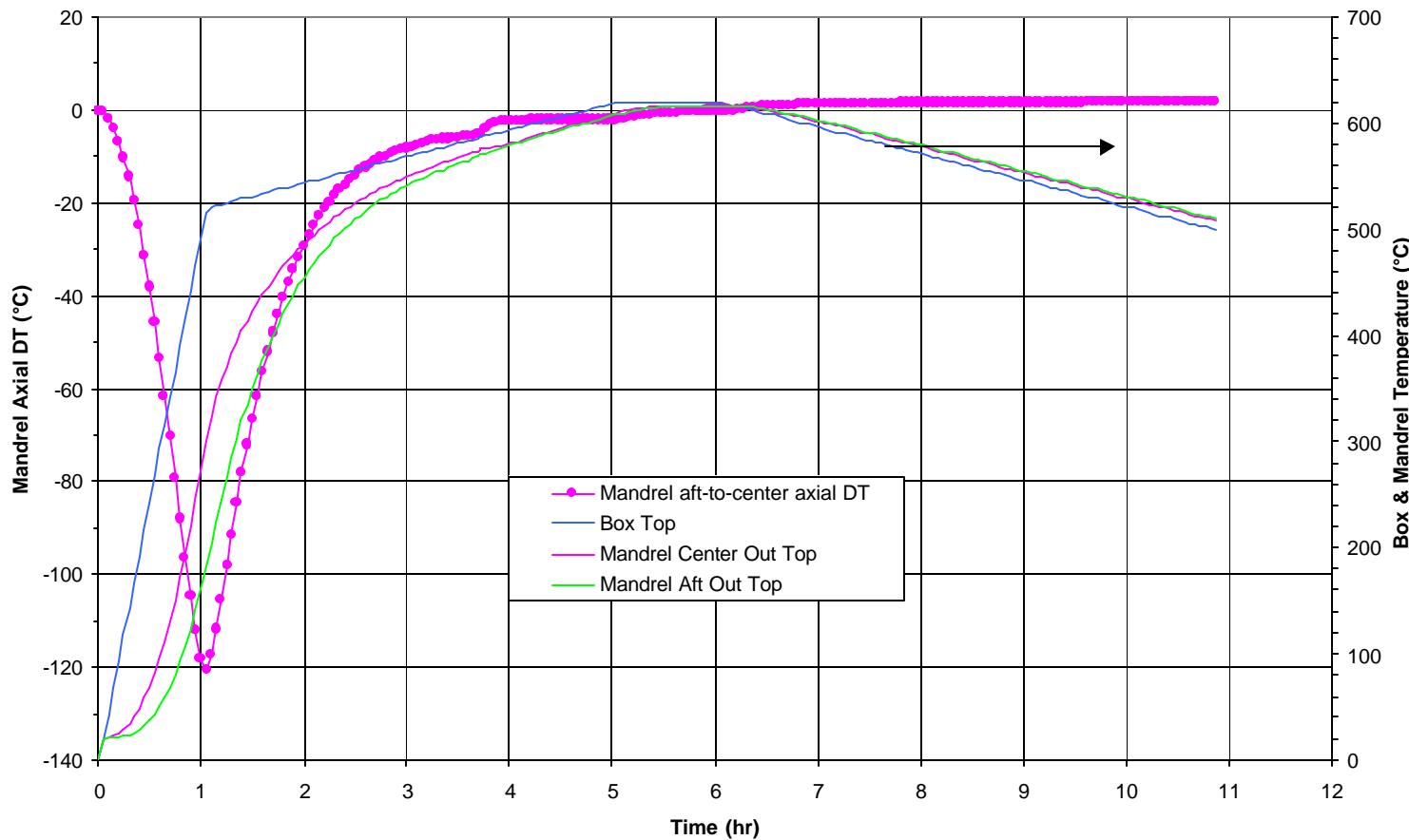


# Mandrel & Glass Temperature Lag to Box Temperature Change



- The box is the heat source. The box temperature change drives the glass & mandrel temperature change.
- The glass center temperature change lags the box temperature change because of the thermal mass.
- The mandrel top temperature change lags the box temperature change because the Mandrel thermal mass is larger, & the glass covers the mandrel top.
- From experiment, the glass slumps when the box reach 580 °C.
- For modeling simplicity, assume the glass instantaneously slumps at 580 °C from flat to completely conformed to the mandrel. The temperature plots show an unrealistic discontinuity at this time. It takes about 30 min for this discontinuity to settle out.

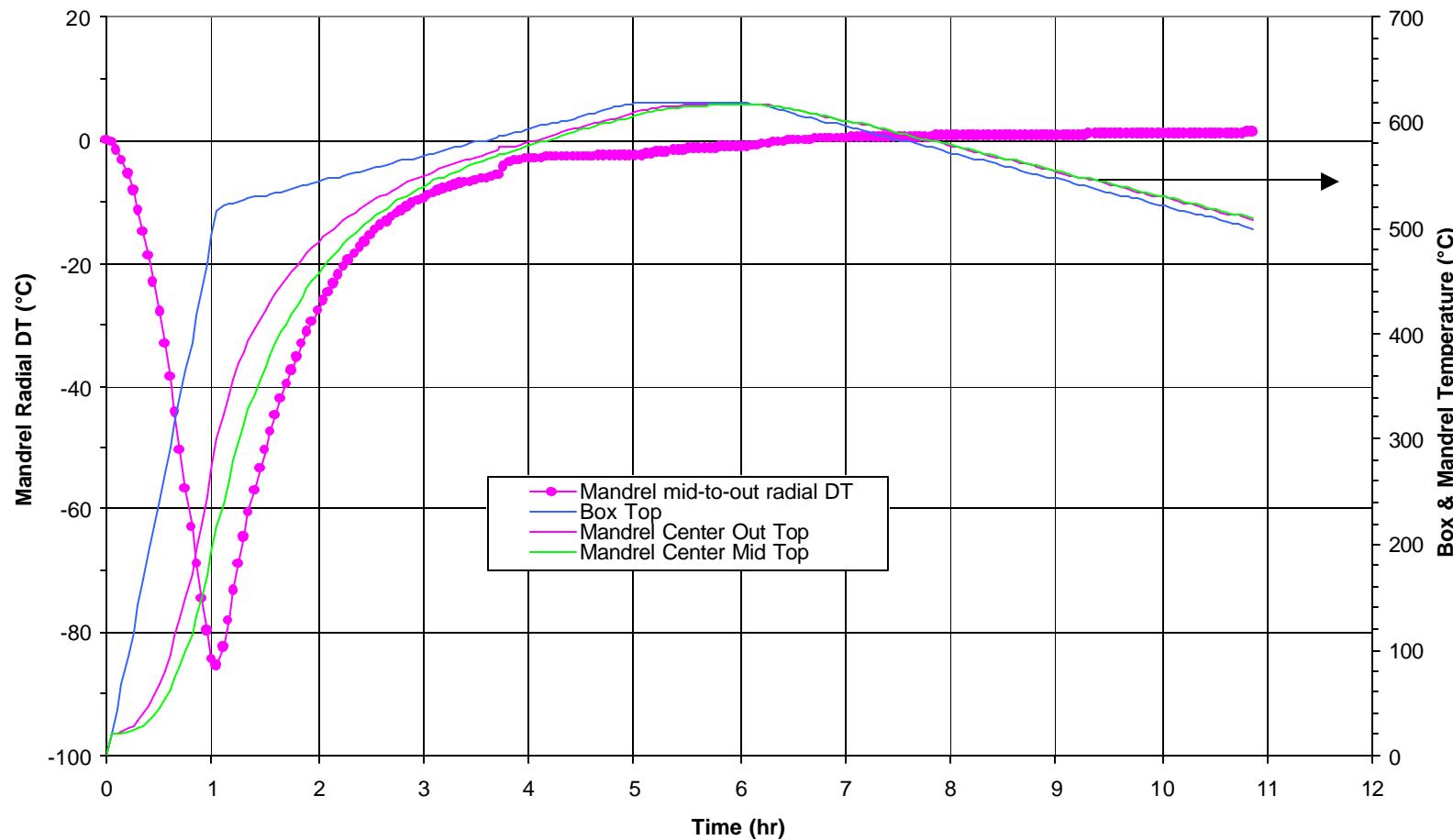
# Mandrel Temperature & Axial DT (P1 of 2)



- In the first hour, the box heats up rapidly ( $520\text{ °C/hr}$ ). During this time the mandrel axial temperature difference increases rapidly. The mandrel center temperature increases faster than mandrel aft temperature. This indicates heating from glass dominates over the thermal mass effect.
- As slumping temperature is approached, the box warm up rate slows down to  $25\text{ °C/hr}$ . The mandrel to box temperature lag decreases, and heating from the glass decreases. This combined effect makes the axial temperature difference drop rapidly.

- With a rapid temperature difference drop, the temperature difference at slumping is much smaller than the peak temperature difference. The small temperature difference is important because it ensures small mandrel distortion as the glass is formed.
- In thermal soak, the constant box temperature allows the mandrel temperatures to catch up. The temperature difference decreases further.
- In cool down, the temperature difference changes little. This indicates that the cool down rate is least important in the glass forming process.

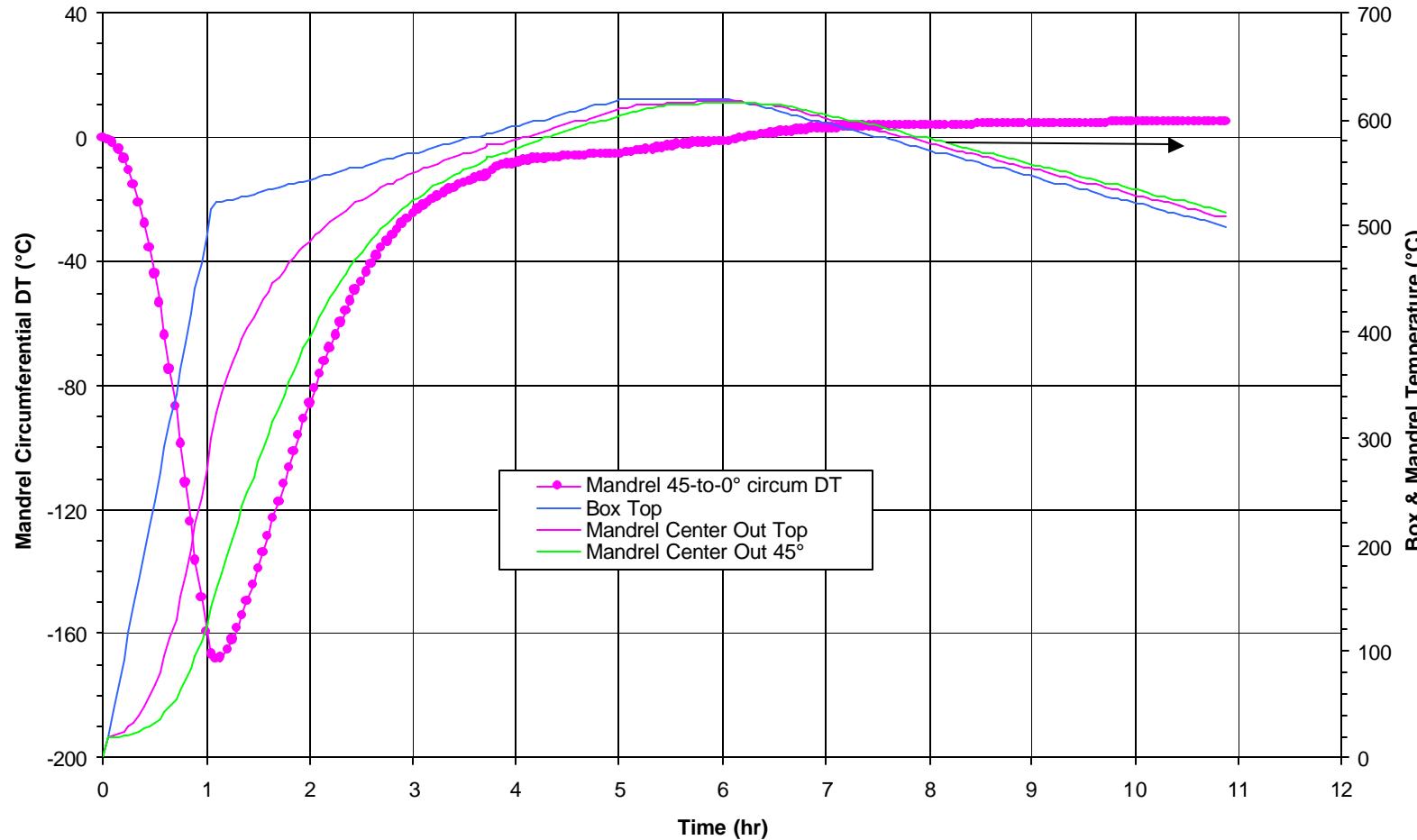
# Mandrel Temperature & Radial DT (P1 of 2)



- In the first hour, the box heats up rapidly ( $520\text{ }^{\circ}\text{C/hr}$ ), the Mandrel radial temperature difference increases rapidly. Mandrel out temperature increases faster than mandrel mid because of heating from glass and the thermal mass effect.

- Because both heating from Glass and the thermal mass effect are driving the temperature difference in the same direction, even though the radial distance is much smaller than the axial distance, the temperature difference in the axial & radial direction are comparable.
- Similar to the axial temperature difference plot, near slumping temperature, the radial temperature difference drops rapidly.
- Small mandrel radial temperature difference at slumping is also important because it also contributes to mandrel distortion.
- Similar to the axial temperature difference plot, in thermal soak, the radial temperature difference decreases further.
- Similar to the axial temperature difference plot, in cool down, the radial temperature difference changes little.

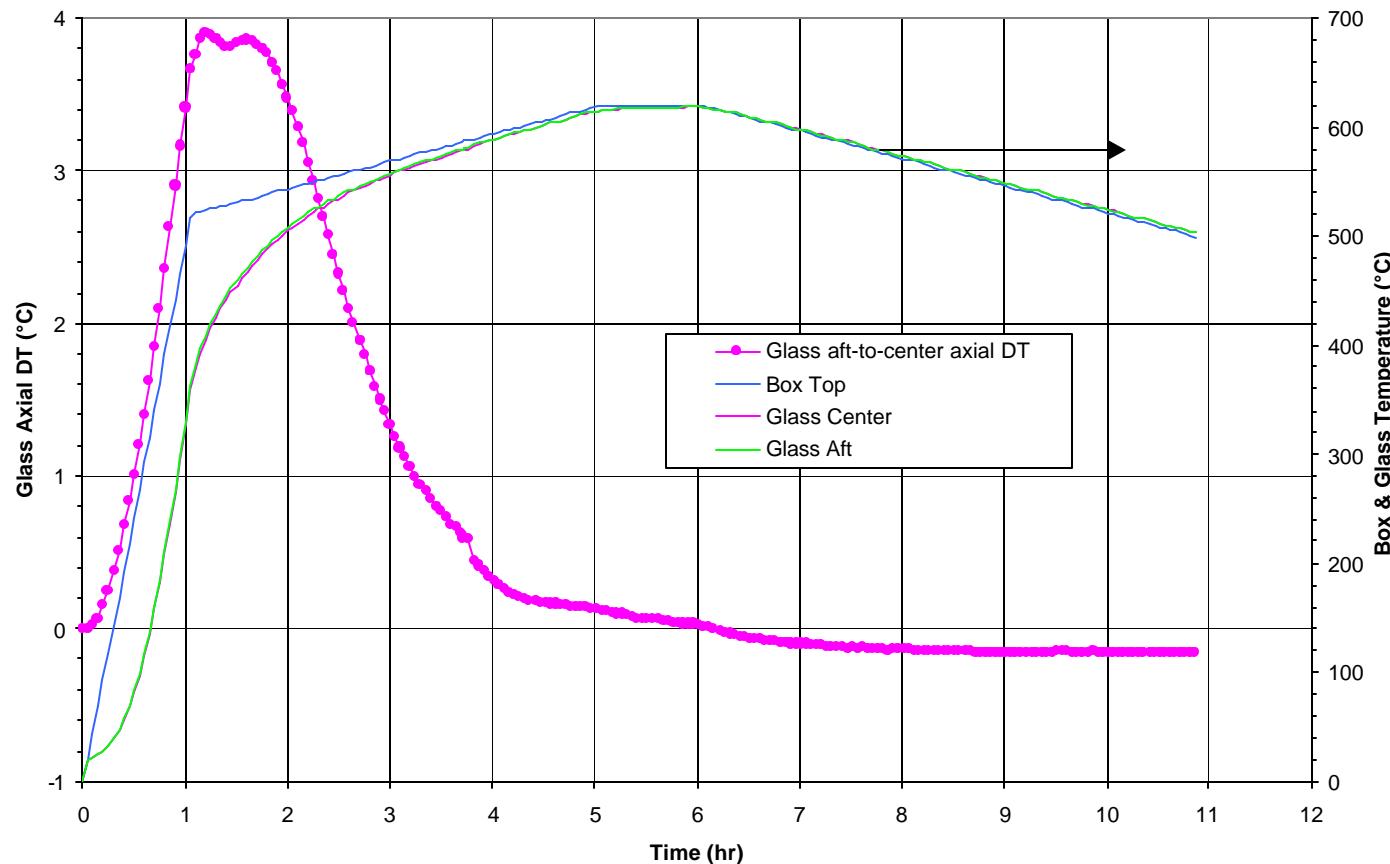
# Mandrel Temperature & Circumferential DT (P1 of 2)



- In the first hour, the box heats up rapidly ( $520\text{ }^{\circ}\text{C/hr}$ ), the mandrel circumferential temperature difference increases rapidly. Mandrel top temperature increases faster than Mandrel at  $45^{\circ}$  because of heating from the glass.
- The temperature difference in the axial, radial, and circumferential direction are all comparable.

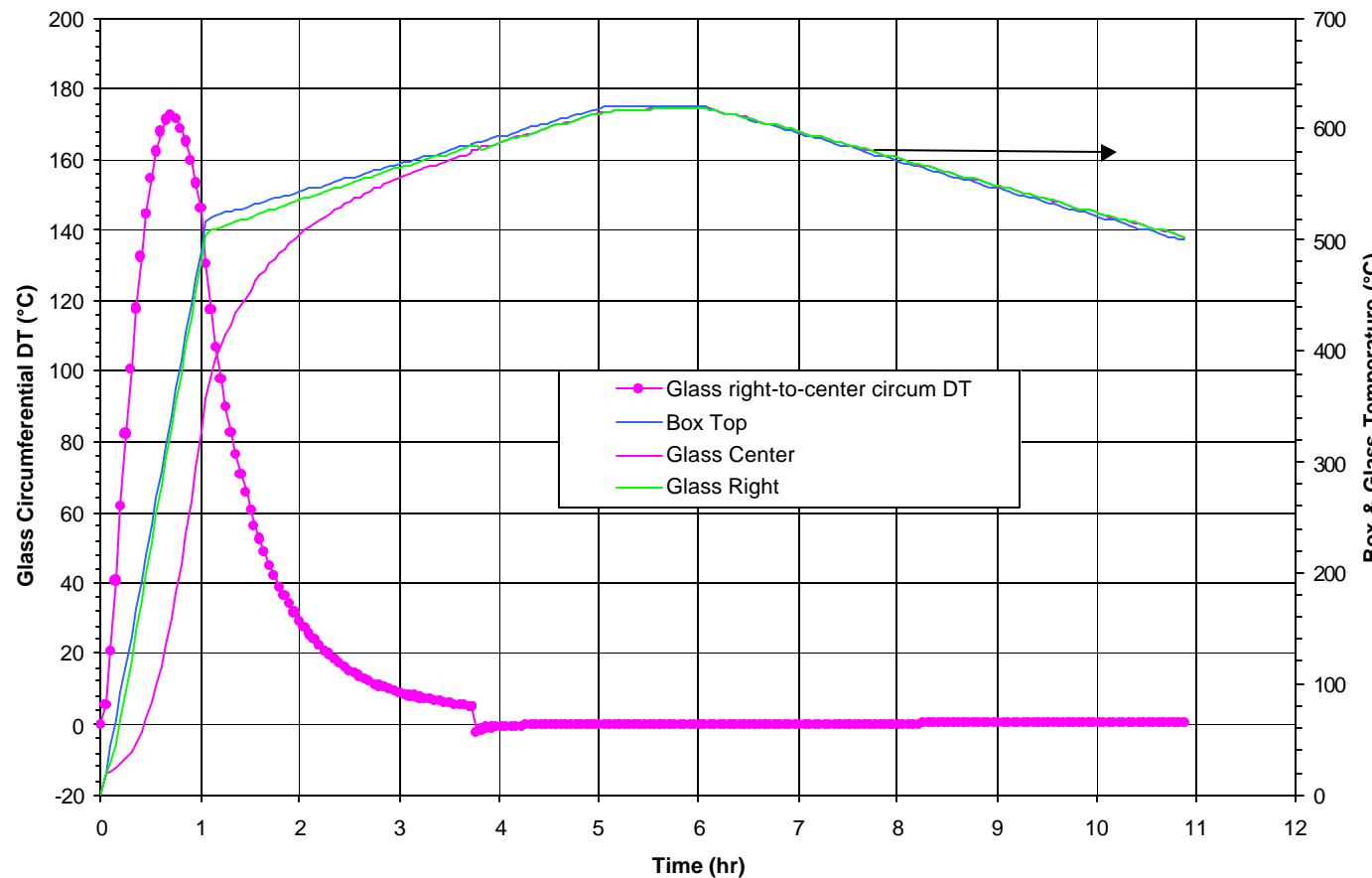
- Similar to the axial temperature difference plot, near slumping temperature, the circumferential temperature difference drops rapidly.
- The small mandrel circumferential temperature difference at slumping is important because it also contributes to mandrel distortion.
- Similar to the axial temperature difference plot, in thermal soak, the circumferential temperature difference decreases further.
- Similar to the axial temperature difference plot, in cool down, the circumferential temperature difference changes little.

# Glass Temperature & Axial DT



- The glass axial temperature difference is much smaller than that of the mandrel.
- On the mandrel side, the edge of the glass has higher view factor to the box than the center. Therefore the glass aft heats up & cools down faster than the glass center.

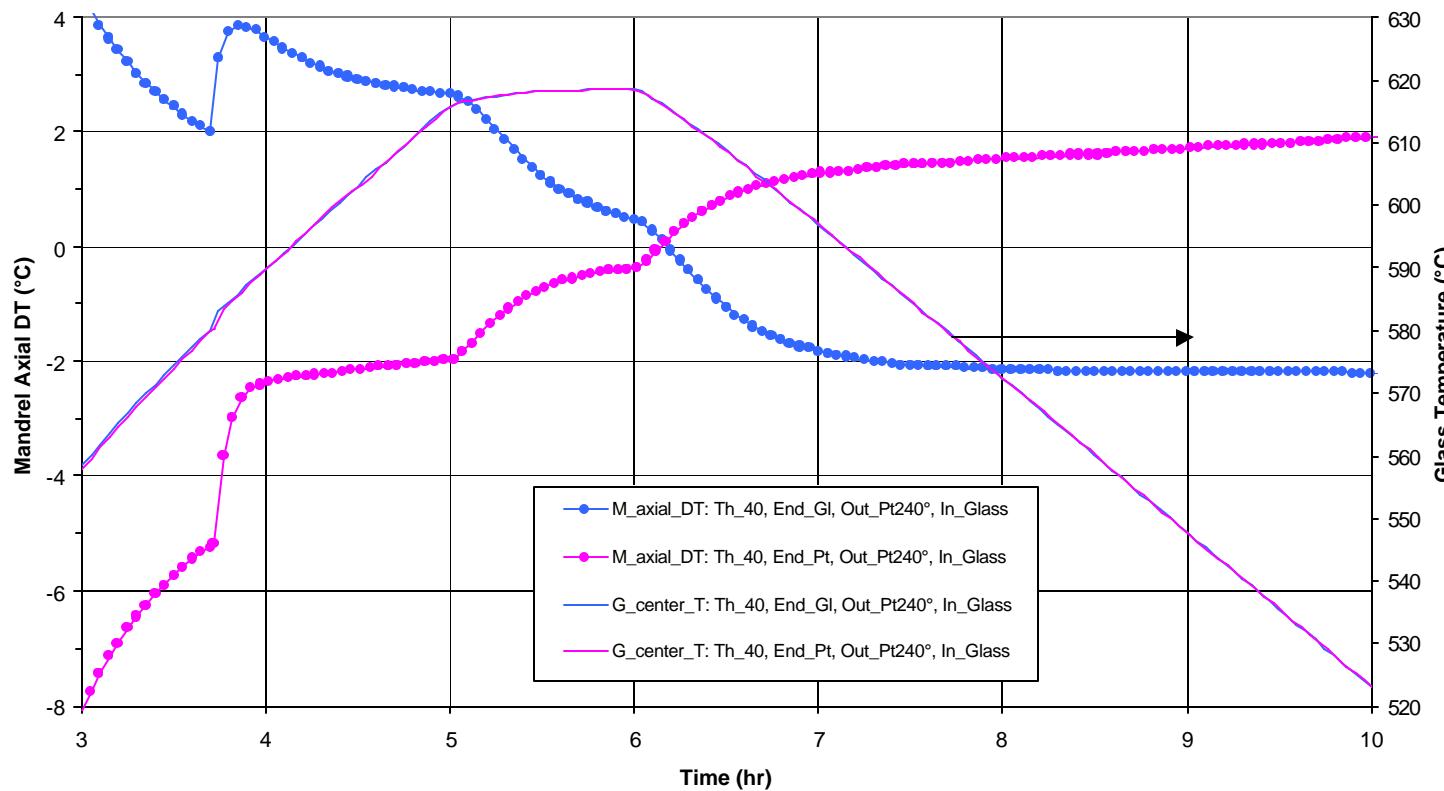
# Glass Temperature & Circumferential DT



- The peak glass circumferential temperature difference is 40 times larger than that of the axial temperature difference.
- On the mandrel side, the lateral edge of the glass has much higher view factor to the box than the center.

- The glass center, because of the large mandrel thermal lag, loses heat to the Mandrel top in heat up mode.
- Combining these 2 factors, the glass edge heats up much faster than the glass center, resulting in very large circumferential temperature difference.
- Near slumping temperature, the box warm up rate slows down significantly. This allows the glass circumferential temperature difference to drop down rapidly before reaching the slumping temperature.
- This rapid reduction of temperature difference is extremely important for the glass also. If not, the edge would gradually exceed the slumping temperature while the center was still significantly below the slumping temperature. The edge would start to fall down even when the center experienced a larger bending moment. Eventually the edge would touch the mandrel first and stick to it, creating ripples between the edge and the center after slumping.
- In cool down, similar to the mandrel temperature difference, the glass temperature difference changes little. Therefore the cool down rate is not as important in the glass forming process.

# Effect of Coating Mandrel Ends on Mandrel Axial DT

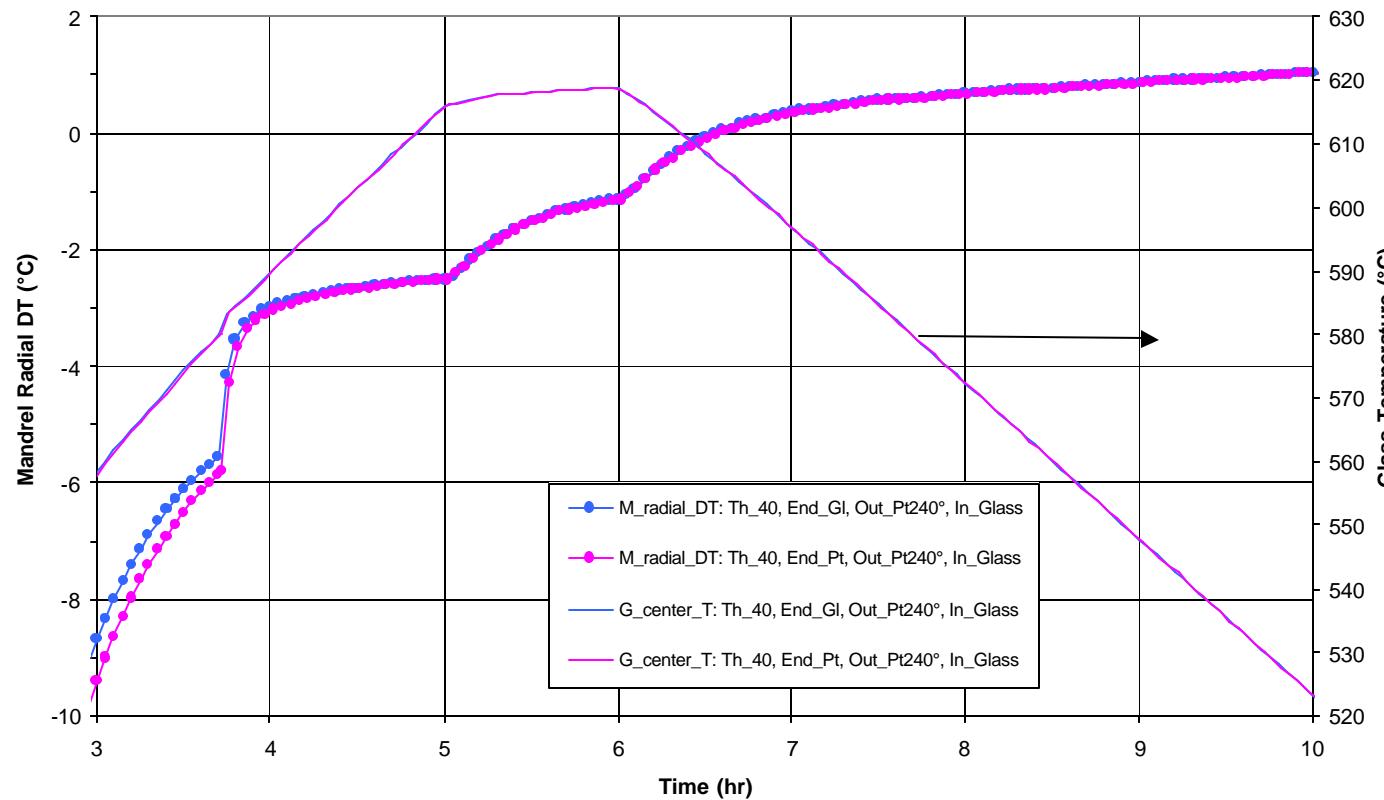


Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Axial DT = -2.3 °C for Pt Ends, = 3.7 °C for Glass Ends  
 $\Rightarrow$  Pt Coating Mandrel Ends reduces Axial DT by 1.4 °C.

Mandrel temperature difference jumps when the glass increases to 580 °C. This is because in the model, the glass slumps from flat to completely conformed to the mandrel instantaneously at 580 °C. To avoid comparing results at the point of discontinuity, we pick 590 °C to compare effect of change in parametric study. At 590 °C, the artificially large change in temperature settles out.

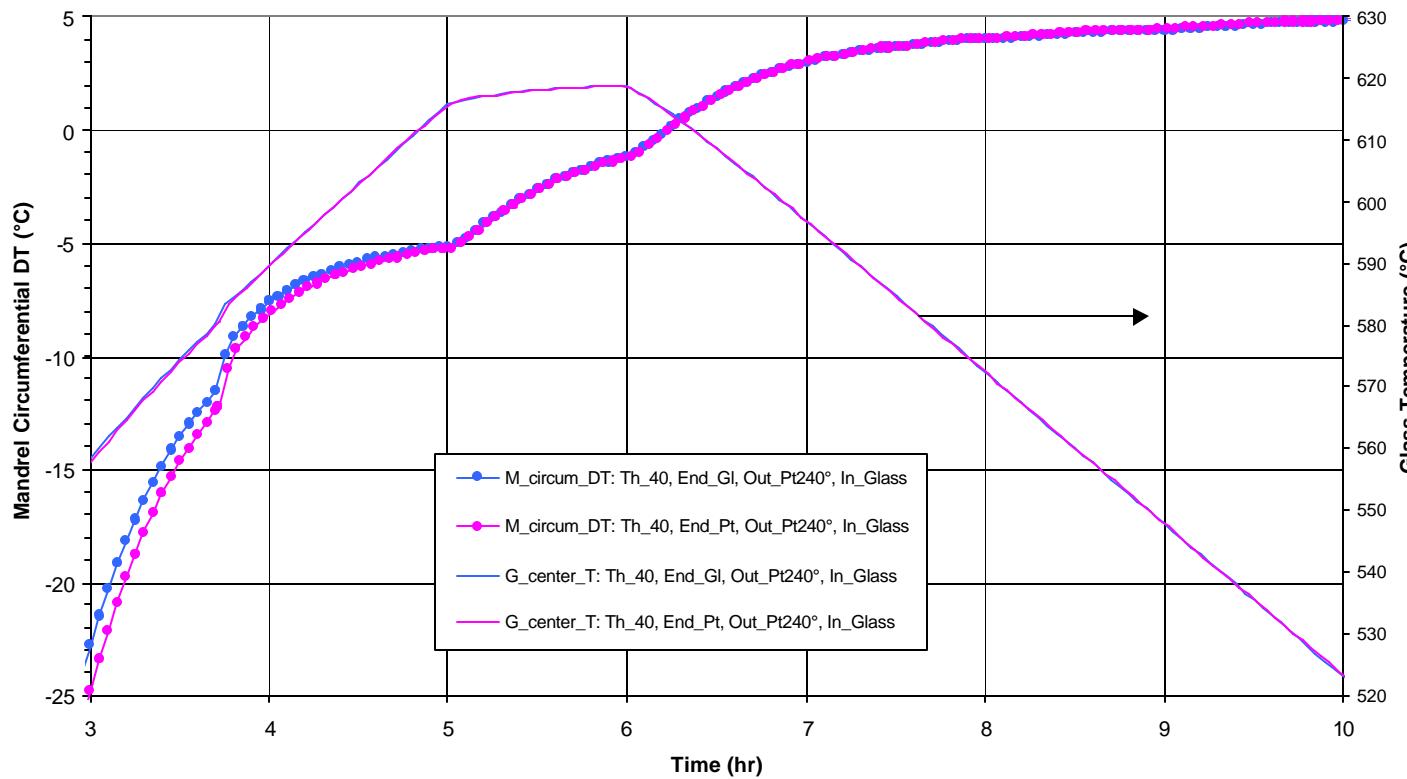
# Effect of Coating Mandrel Ends on Mandrel Radial DT



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center = 590  $^{\circ}\text{C}$ , Mandrel Radial DT = -3.0  $^{\circ}\text{C}$  for Pt Ends, = -3.0  $^{\circ}\text{C}$  for Glass Ends  
=> Pt Coating Mandrel Ends have negligible effect on Radial DT.

# Effect of Coating Mandrel Ends on Mandrel Circum DT

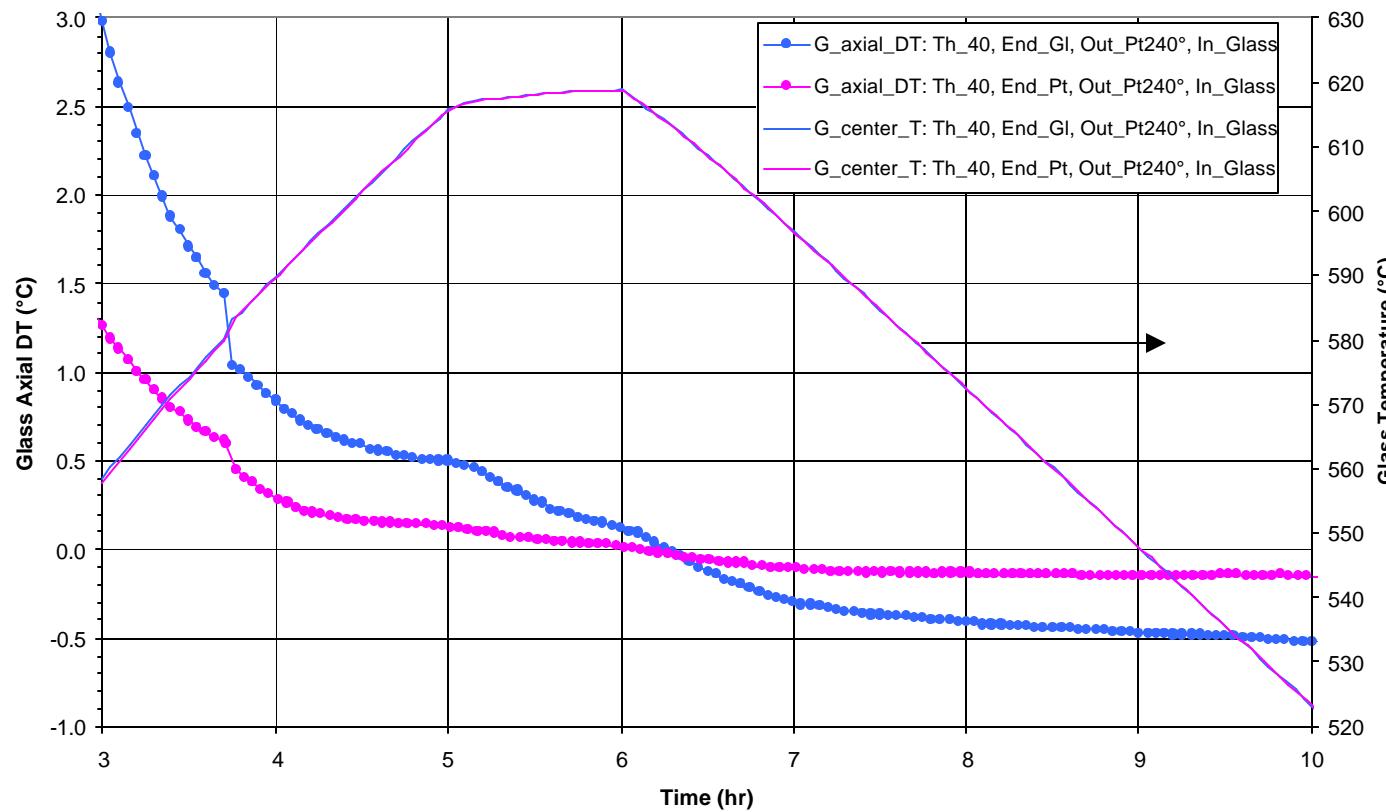


Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location: 45° to 0°

Glass Center = 590 °C, Mandrel Circum DT = -8.0 °C for Pt Ends, = -7.6 °C for Glass Ends  
⇒ Pt Coating Mandrel Ends increase Circum DT slightly.

Pt coating mandrel ends decreases axial DT significantly, but increases radial & circum DT slightly.  
Low emissivity coating reduces end effects, so it decreases axial DT.  
Low emissivity coating also decreases the radiative heating. It slows down the equilibrating process, so the radial & circum DT is slightly higher.

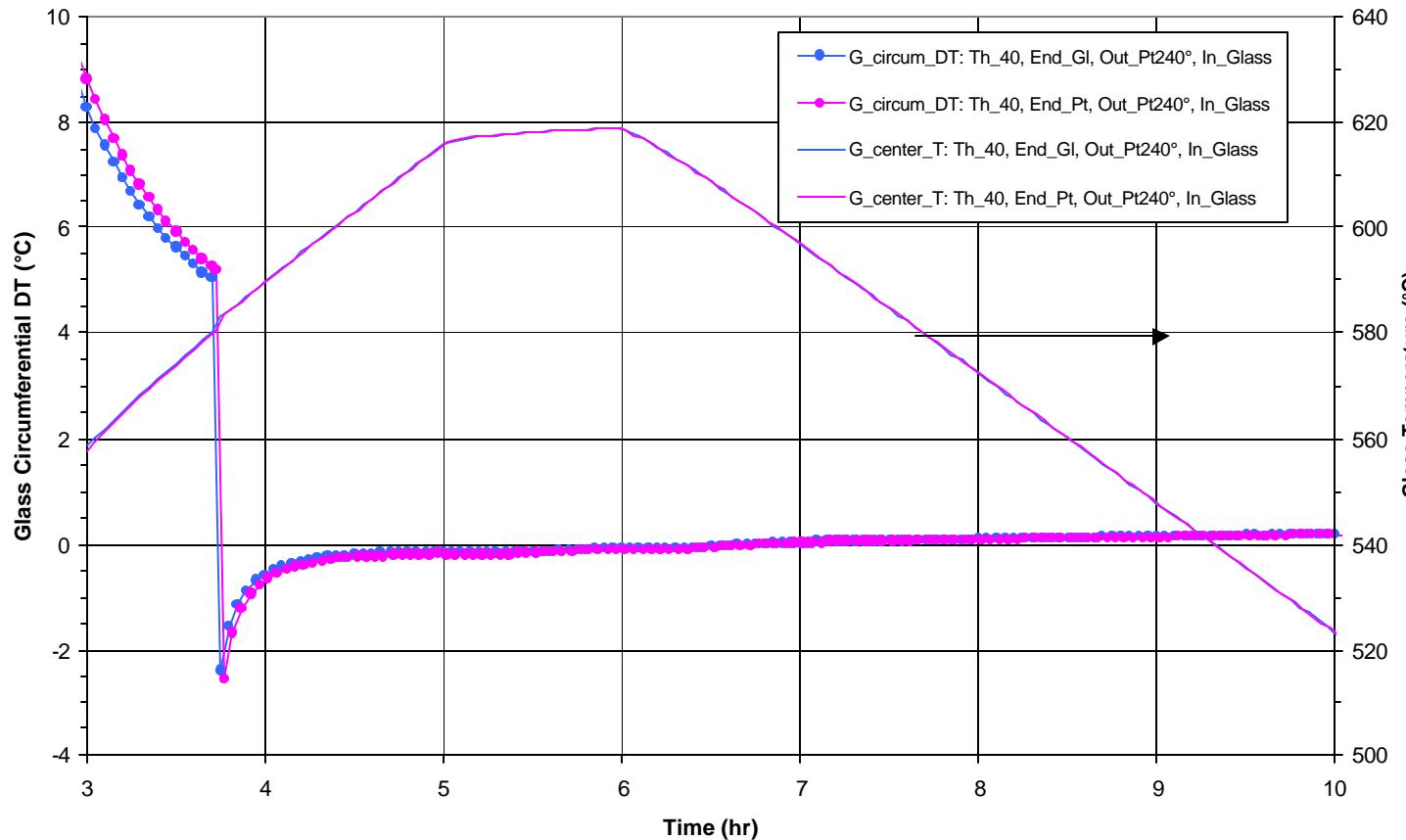
# Effect of Coating Mandrel Ends on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.3 °C for Pt Ends, = 0.8 °C for Glass Ends  
 ⇒ Pt coating mandrel ends reduces glass axial DT by 0.5 °C.

# Effect of Coating Mandrel Ends on Glass Circum DT

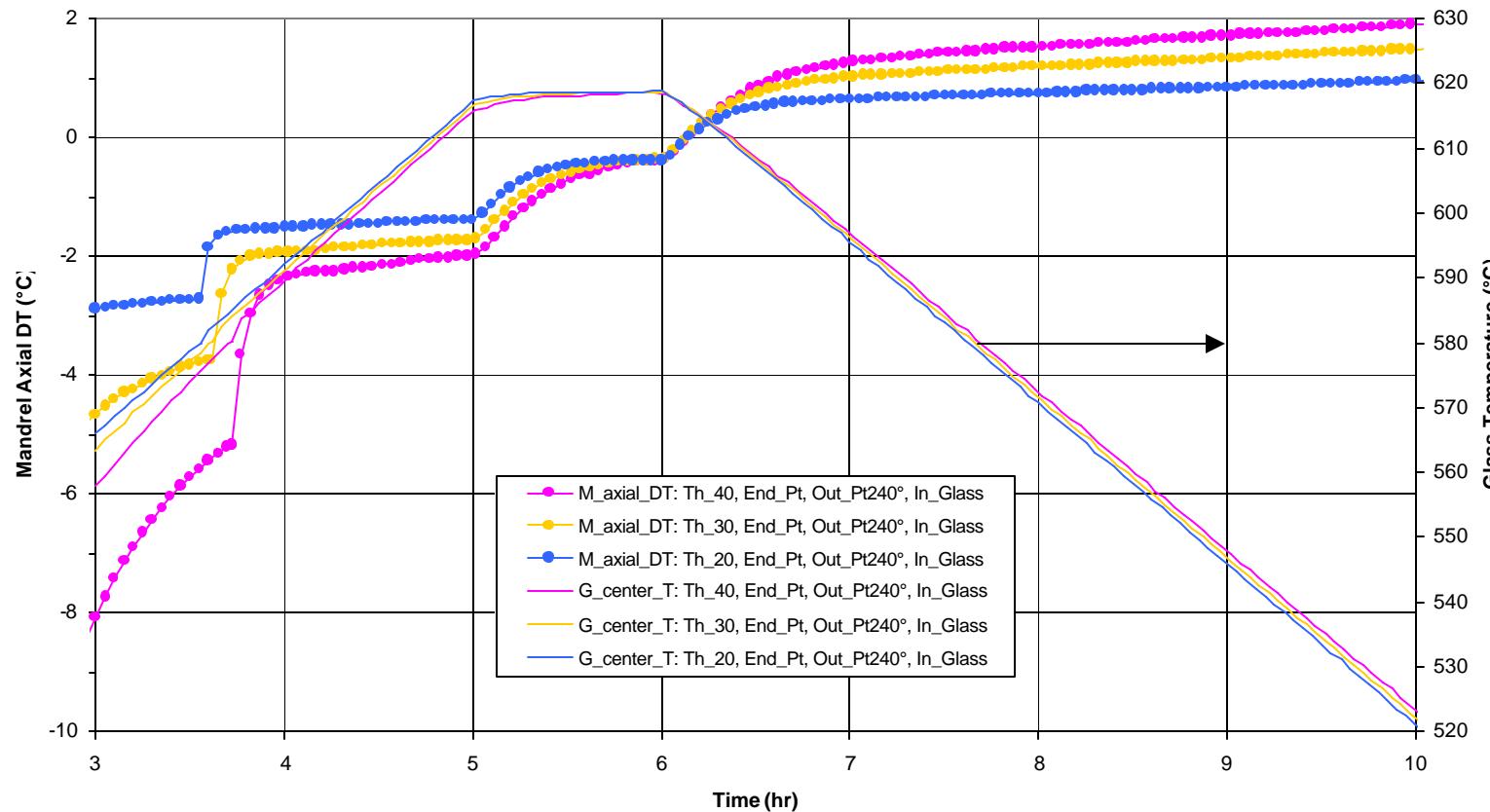


Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for Pt Ends, = -0.6 °C for Glass Ends  
⇒ Pt coating mandrel ends has a negligible effect on glass circum DT.

Glass circum DT drops sharply when glass increases to 580 °C. This is because in the model, the glass slumps from flat to completely conformed to Mandrel instantaneously at 580 °C. The hot glass edge loses heat to the much colder Mandrel suddenly, resulting in a large drop in the glass edge temperature.

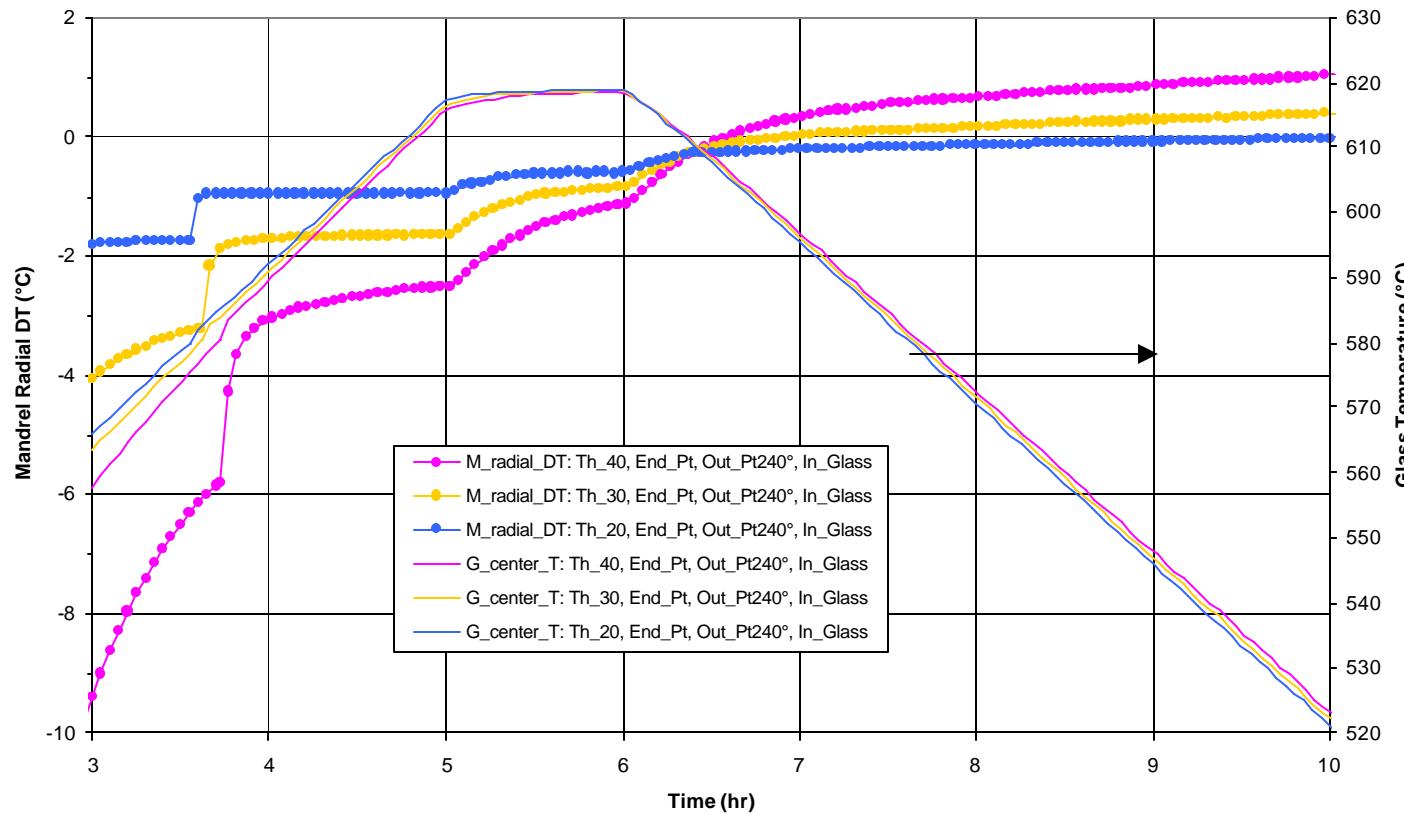
# Effect of Mandrel Thickness on Mandrel Axial DT



Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Axial DT =  $-2.3\text{ }^{\circ}\text{C}$  for 40 mm, =  $-1.9\text{ }^{\circ}\text{C}$  for 30 mm, =  $-1.5\text{ }^{\circ}\text{C}$  for 20 mm  
 ⇒ Reducing mandrel thickness from 40 to 20 mm reduces axial DT by  $0.8\text{ }^{\circ}\text{C}$ .

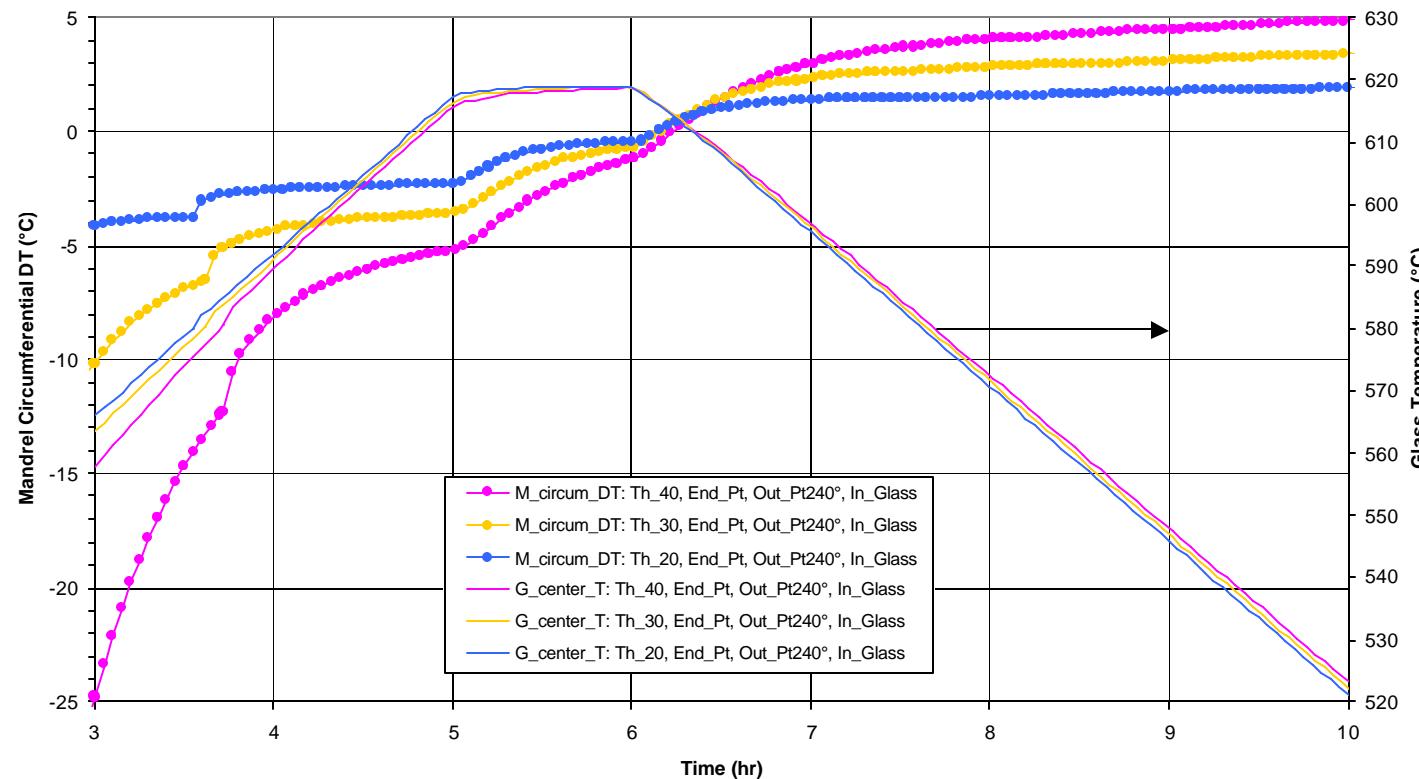
# Effect of Mandrel Thickness on Mandrel Radial DT



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Radial DT =  $-3.0\text{ }^{\circ}\text{C}$  for 40 mm, =  $-1.7\text{ }^{\circ}\text{C}$  for 30 mm, =  $-1.0\text{ }^{\circ}\text{C}$  for 20 mm  
 $\Rightarrow$  Reducing mandrel thickness from 40 to 20 mm reduces radial DT by  $2.0\text{ }^{\circ}\text{C}$ .

# Effect of Mandrel Thickness on Mandrel Circum DT



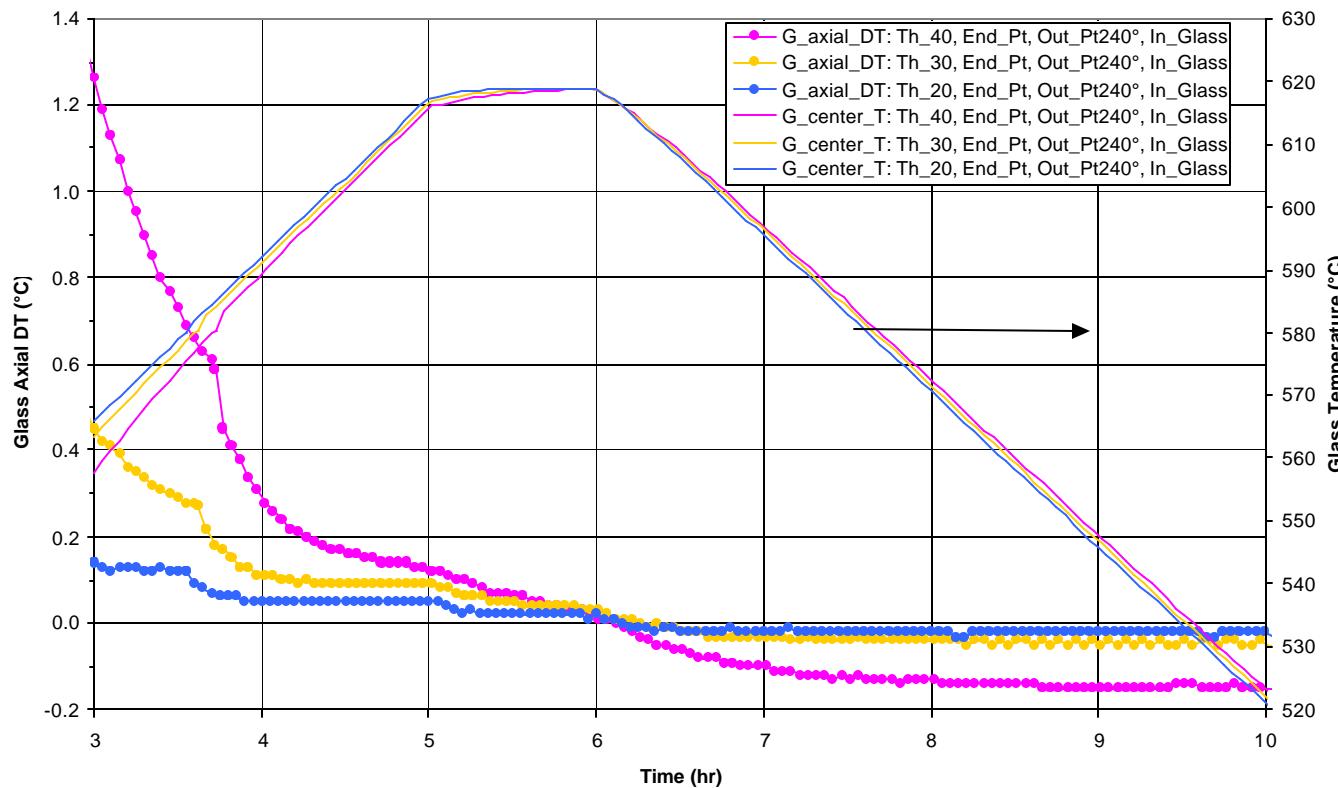
Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location: 45° to 0°

Glass Center = 590 °C, Mandrel Circum DT = -8.0 °C for 40 mm, = -4.4 °C for 30 mm, = -2.6 °C for 20 mm  
 ⇒ Reducing mandrel thickness from 40 to 20 mm reduces circum DT by 5.4 °C.

Reducing mandrel thickness reduces DT in axial, radial, & circum directions significantly.

Reducing mandrel thickness reduces thermal mass, thus speeding up thermal equilibrium. It is very desirable thermally. However, the thinner Mandrel is weaker structurally. The optimum thickness is a balance between thermal and structural to get the least distortion.

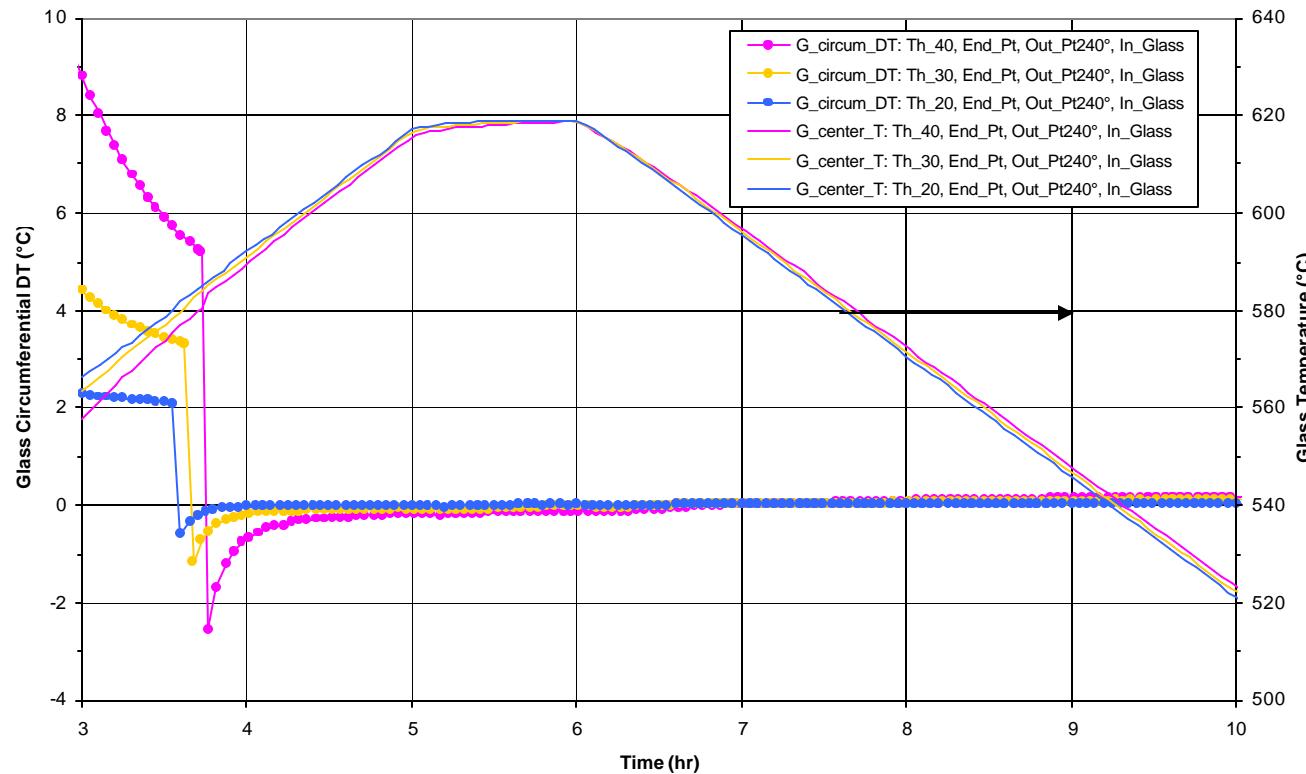
# Effect of Mandrel Thickness on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.28 °C for 40 mm, = 0.11 °C for 30 mm, = 0.05 °C for 20 mm  
 ⇒ Reducing mandrel thickness from 40 to 20 mm reduces glass axial DT by 0.23 °C.

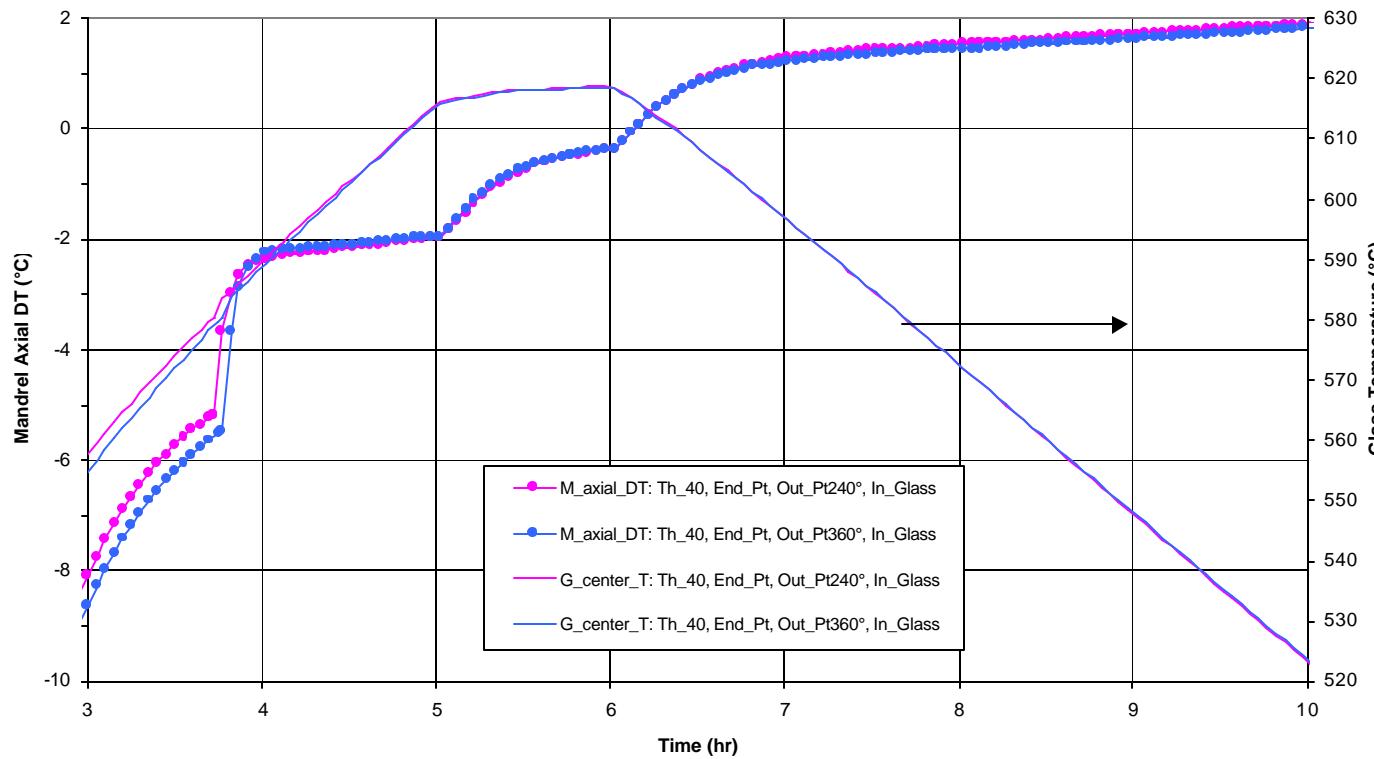
# Effect of Mandrel Thickness on Glass Circum DT



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.65 °C for 40 mm, = -0.20 °C for 30 mm, = -0.05 °C for 20 mm  
 ⇒ Reducing mandrel thickness from 40 to 20 mm reduce glass circum DT by 0.6 °C.

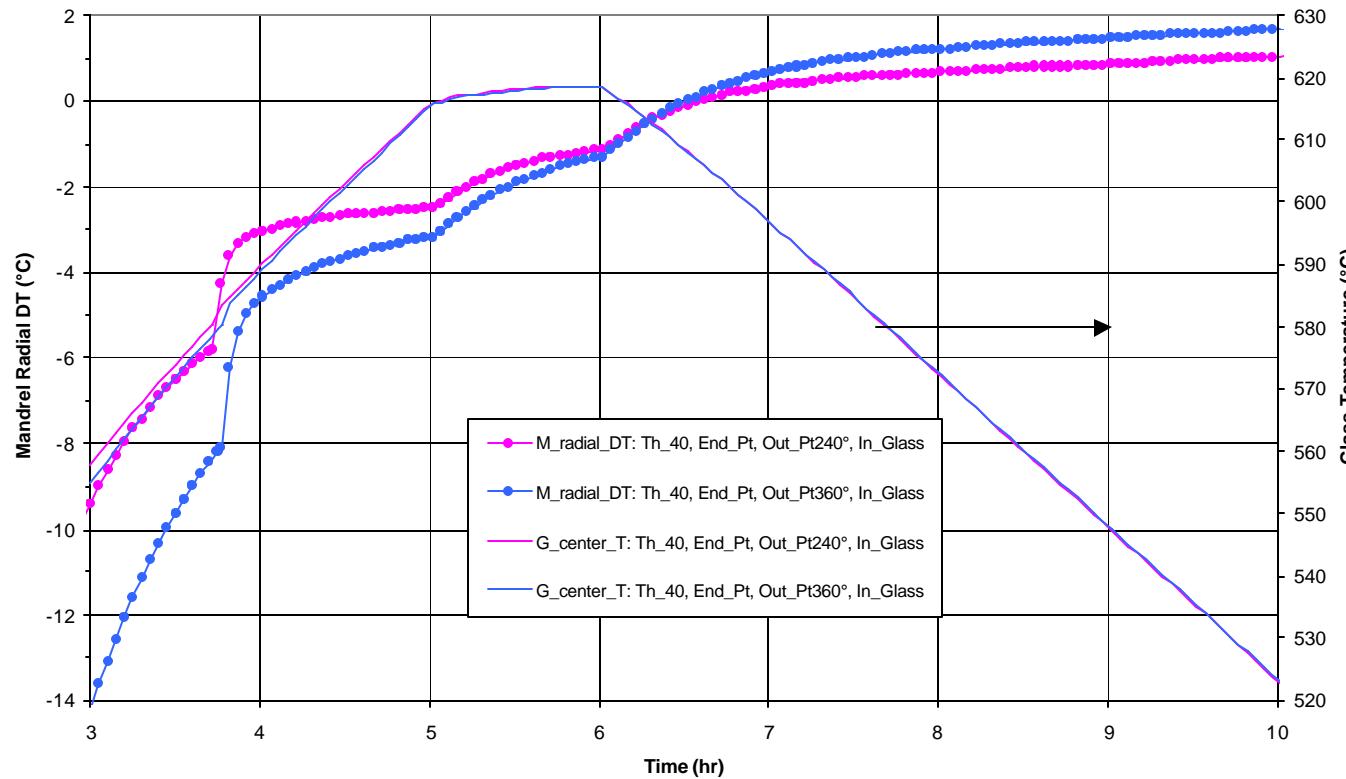
# Effect of Pt Coverage on Mandrel Axial DT



Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590^{\circ}\text{C}$ , Mandrel Axial DT =  $-2.3^{\circ}\text{C}$  for  $240^{\circ}$  Coverage, =  $-2.2^{\circ}\text{C}$  for  $360^{\circ}$  Coverage  
⇒ Increasing Pt coverage on the mandrel outside surface reduces Axial DT slightly.

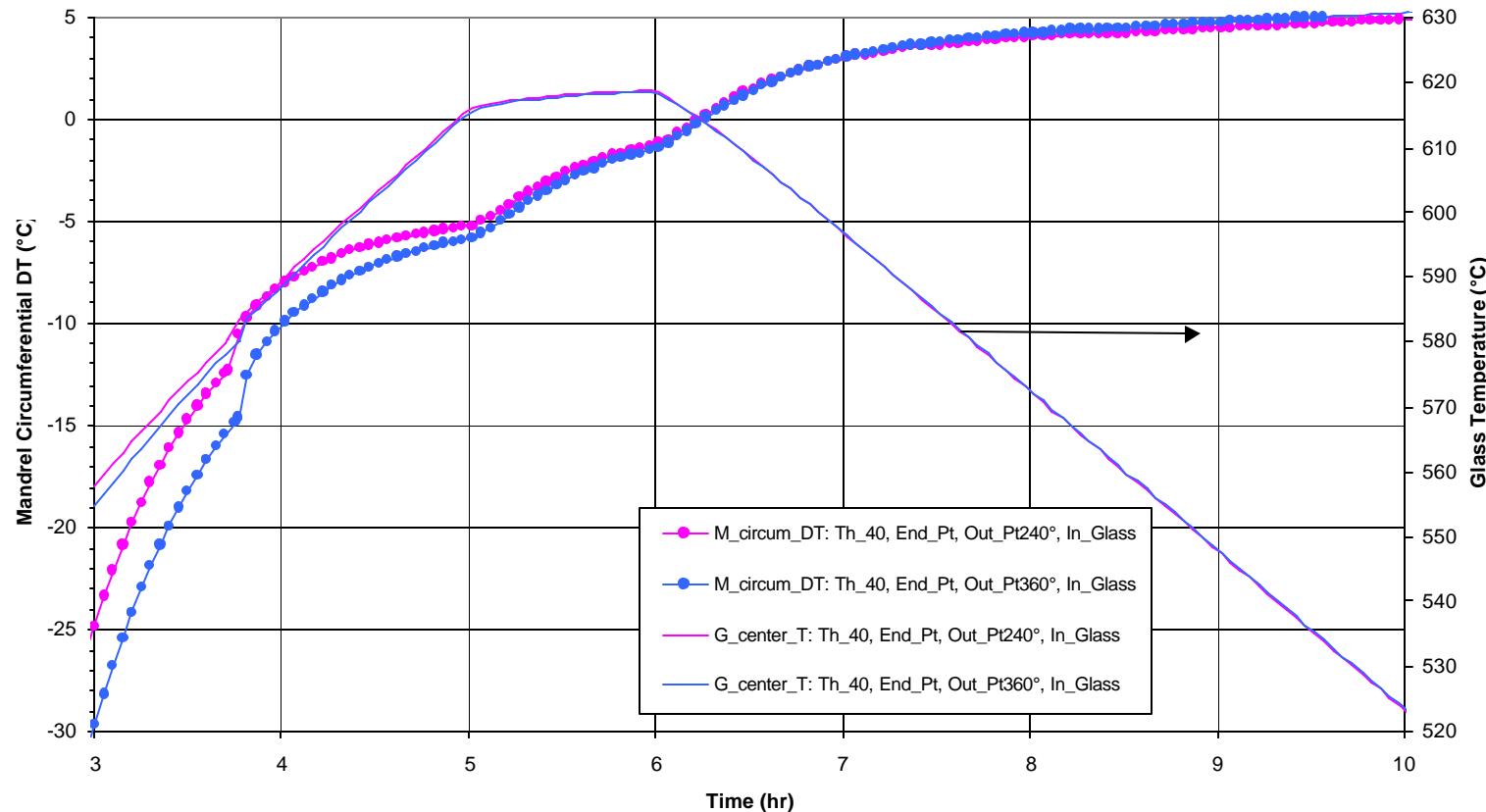
# Effect of Pt Coverage on Mandrel Radial DT



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Radial DT = -3.0 °C for 240° Coverage, = -4.6 °C for 360° Coverage  
⇒ Increasing Pt coverage on the mandrel outside surface increases radial DT by 1.6 °C.

# Effect of Pt Coverage on Mandrel Circum DT



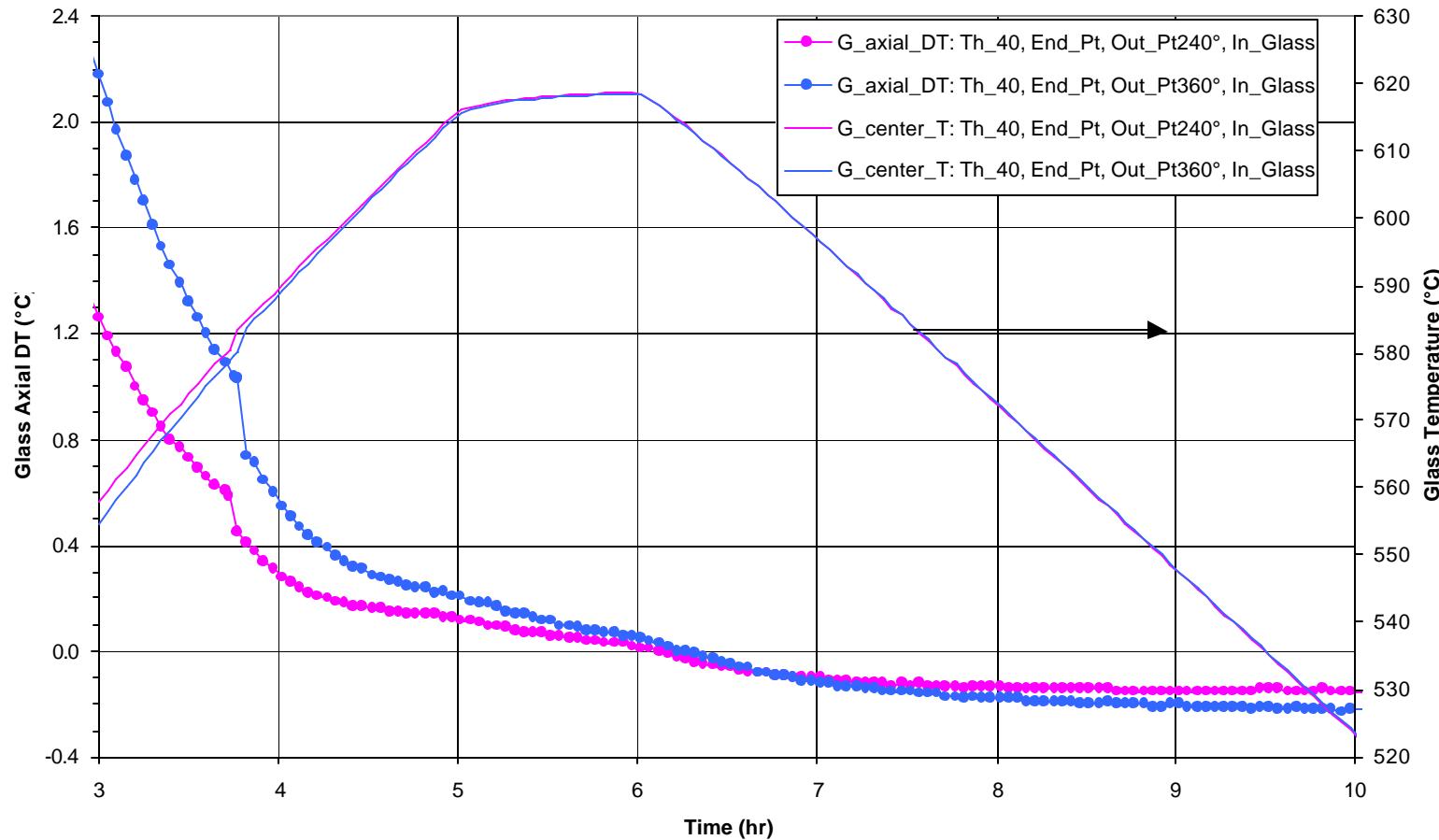
Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location:  $0^{\circ}$  to  $45^{\circ}$

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Circum DT =  $-8.0\text{ }^{\circ}\text{C}$  for  $240^{\circ}$  Coverage, =  $-9.9\text{ }^{\circ}\text{C}$  for  $360^{\circ}$  Coverage  
 $\Rightarrow$  Increasing Pt coverage on the mandrel outside surface increase circum DT by  $1.9\text{ }^{\circ}\text{C}$ .

Increasing Pt coverage actually increases radial & circum DT. It is worse off.

Increasing Pt coverage to  $360^{\circ}$  should have removed the unsymmetrical effect circumferentially. However, this effect is dominated by slower equilibrium in larger low emissivity coverage, resulting in a larger DT.

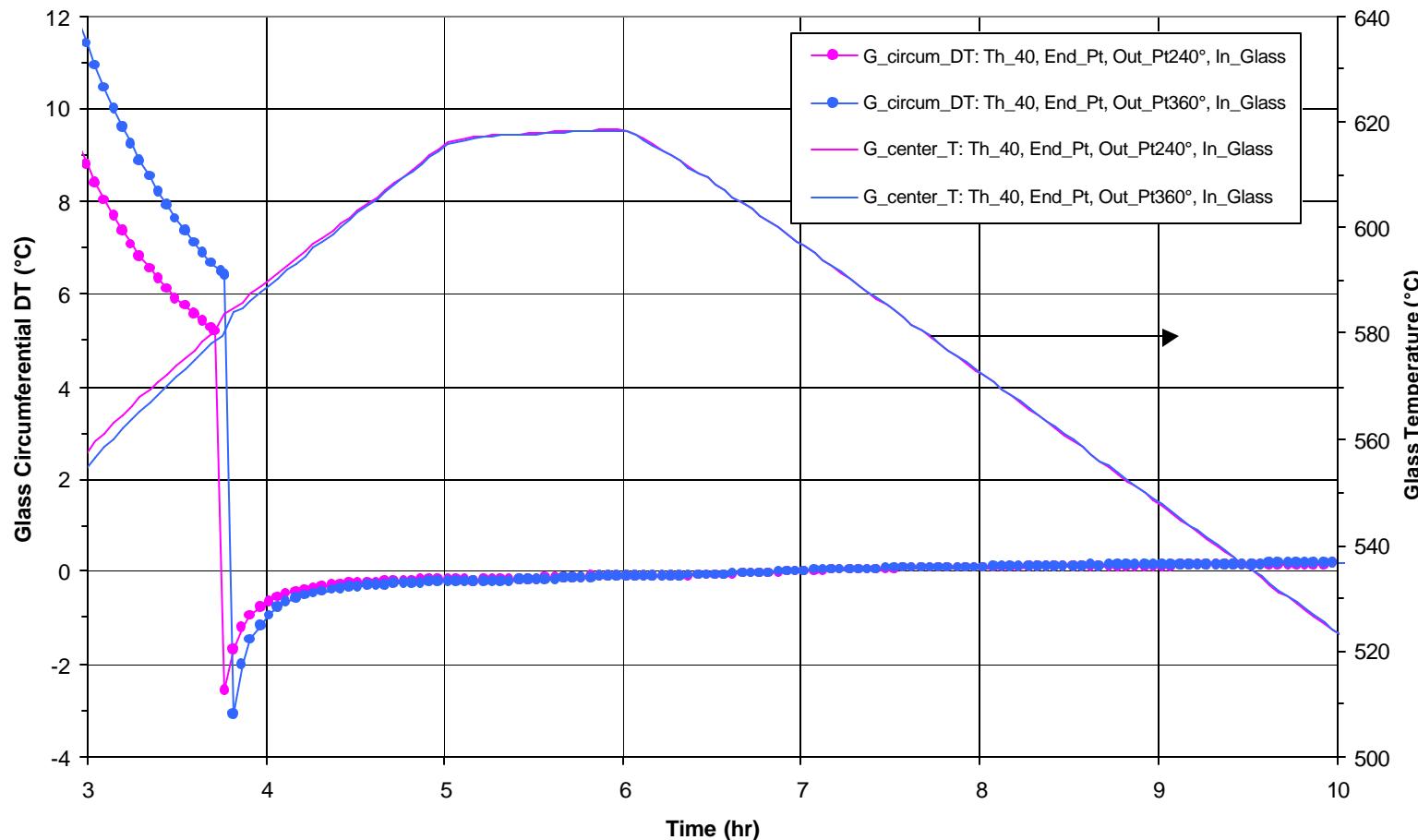
# Effect of Pt Coverage on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.3 °C for 240° Coverage, = 0.6 °C for 360° Coverage  
 ⇒ Increasing Pt coverage on the mandrel outside surface increase glass axial DT by 0.3 °C.

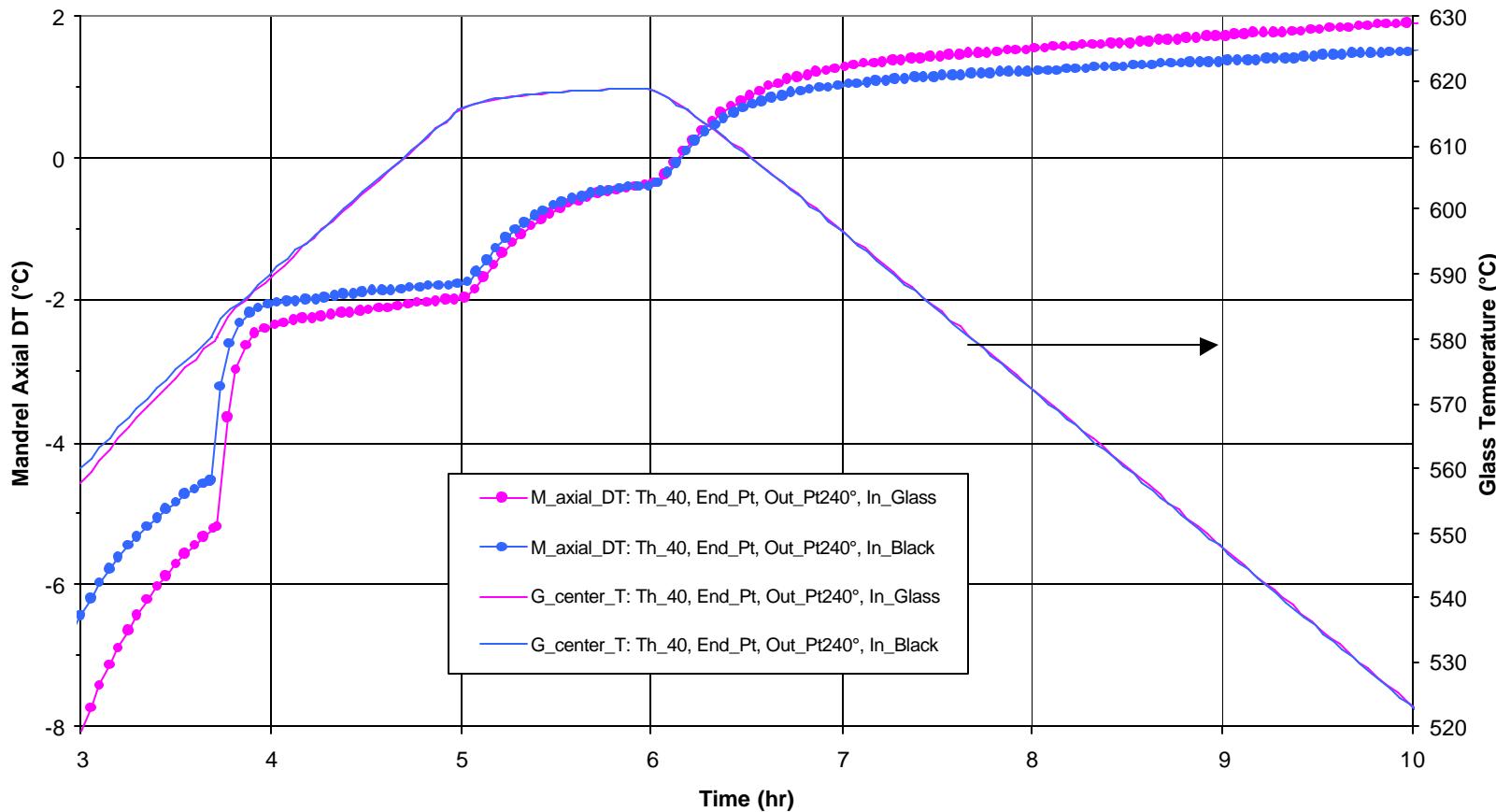
# Effect of Pt Coverage on Glass Circum DT



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for 240° Coverage,      = -0.9 °C for 360° Coverage  
⇒ Increasing Pt coverage on the mandrel outside surface increases glass circum DT by 0.3 °C.

# Effect of Coating Mandrel Inside Black on Mandrel Axial DT

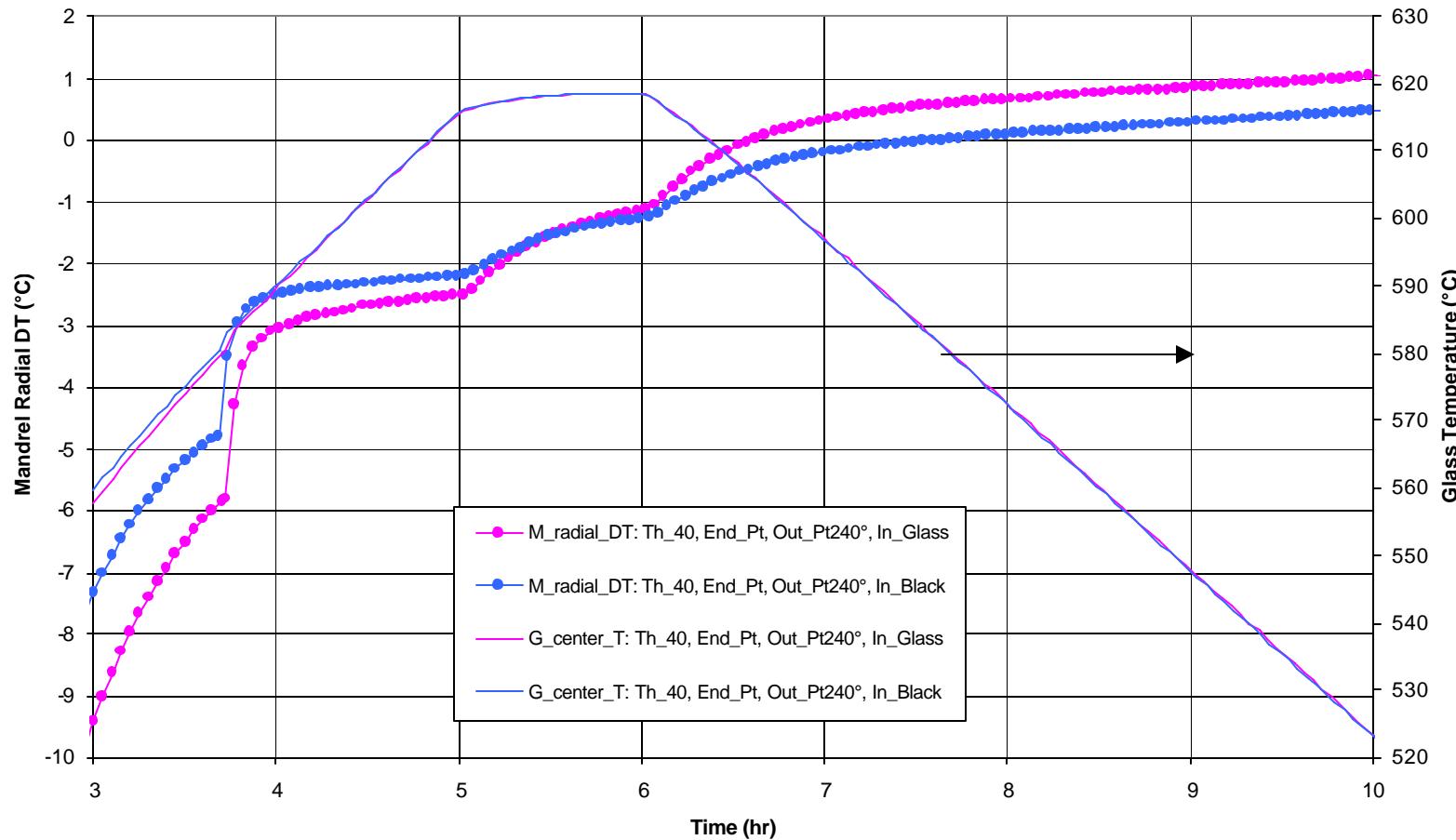


Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Axial DT = -2.3 °C for inside Bare Glass, = -2.1 °C for inside Black  
 ⇒ Coating Mandrel inside black reduces axial DT by 0.3 °C.

# Effect of Coating Mandrel Inside Black on Mandrel Radial DT

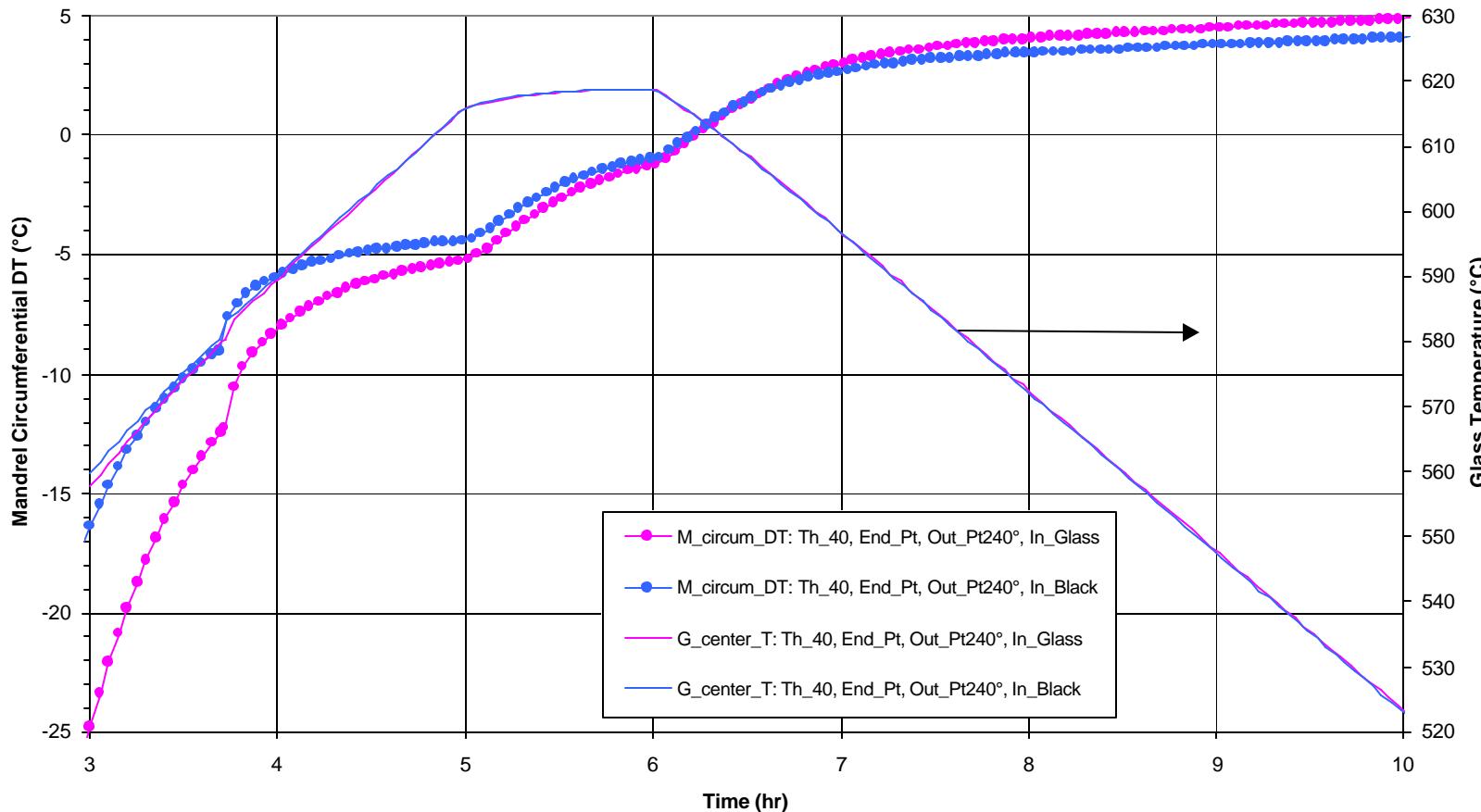
**SWALES**  
AEROSPACE



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Radial DT =  $-3.0\text{ }^{\circ}\text{C}$  for inside Bare Glass, =  $-2.5\text{ }^{\circ}\text{C}$  for inside Black  
 $\Rightarrow$  Coating Mandrel inside black reduces radial DT by  $0.5\text{ }^{\circ}\text{C}$ .

# Effect of Coating Mandrel Inside Black on Mandrel Circum DT



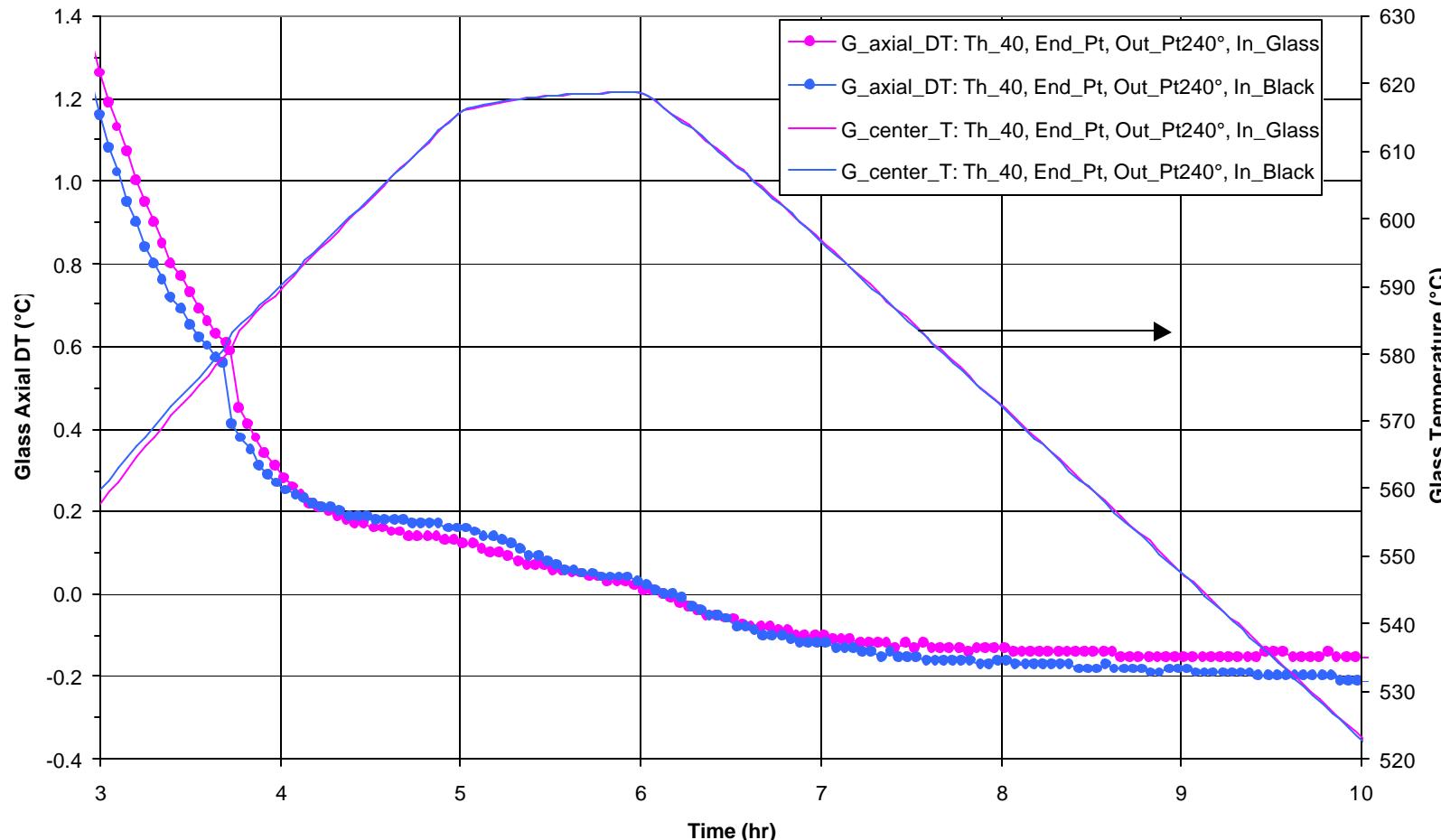
Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location: 45° to 0°

Glass Center = 590 °C, Mandrel Circum DT = -8.0 °C for inside Bare Glass,      = -5.9 °C for inside Black  
⇒ Coating mandrel inside black reduces circum DT by 2.1 °C.

Coating mandrel inside black reduces all DT's because high emissivity coating increases the radiative heating. This speeds up the equilibrating process.

# Effect of Coating Mandrel Inside Black on Glass Axial DT

**SWALES**  
AEROSPACE

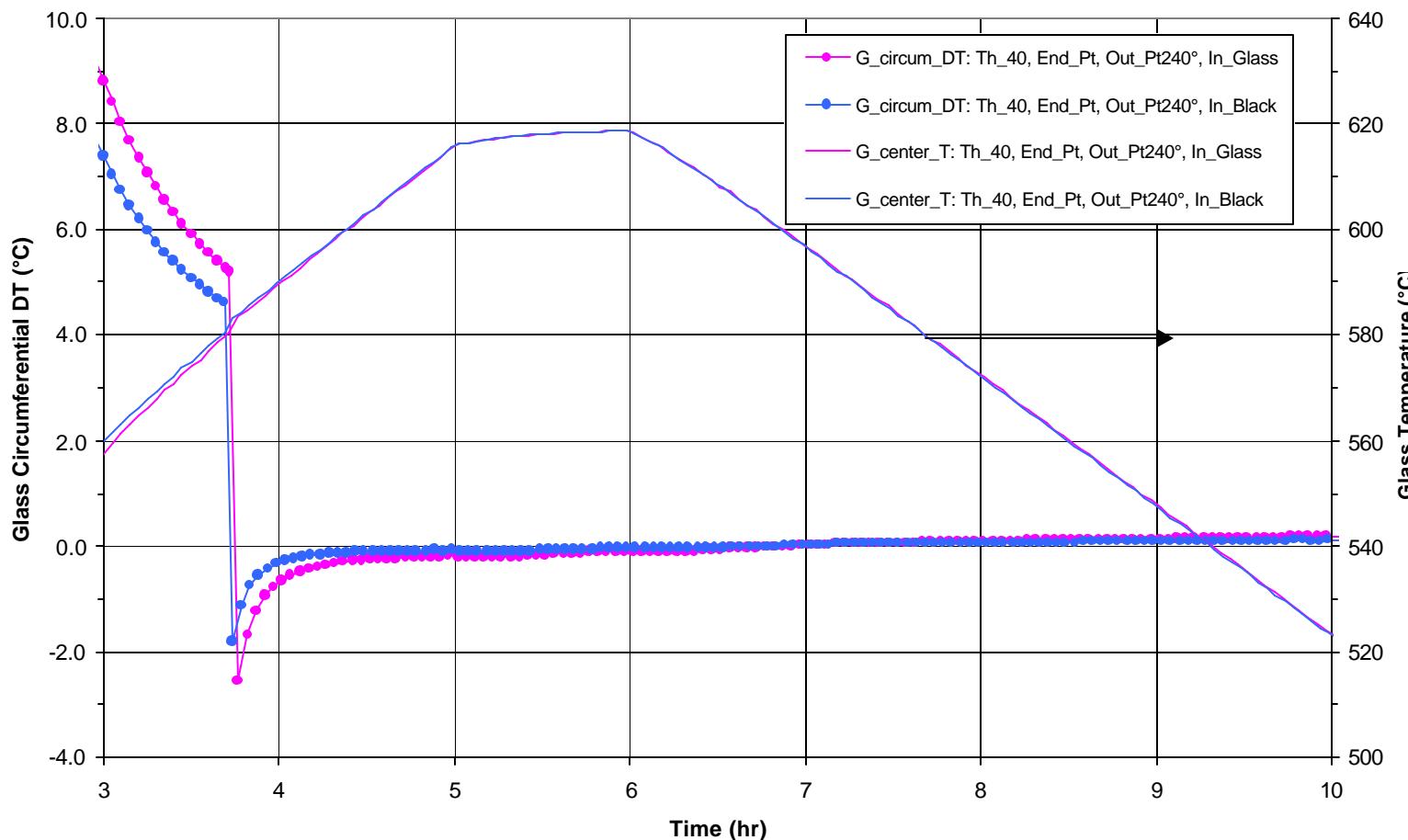


Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.28 °C for inside Bare Glass,  
 ⇒ Coating mandrel inside black reduces glass axial DT slightly.

# Effect of Coating Mandrel Inside Black on Glass Circum DT

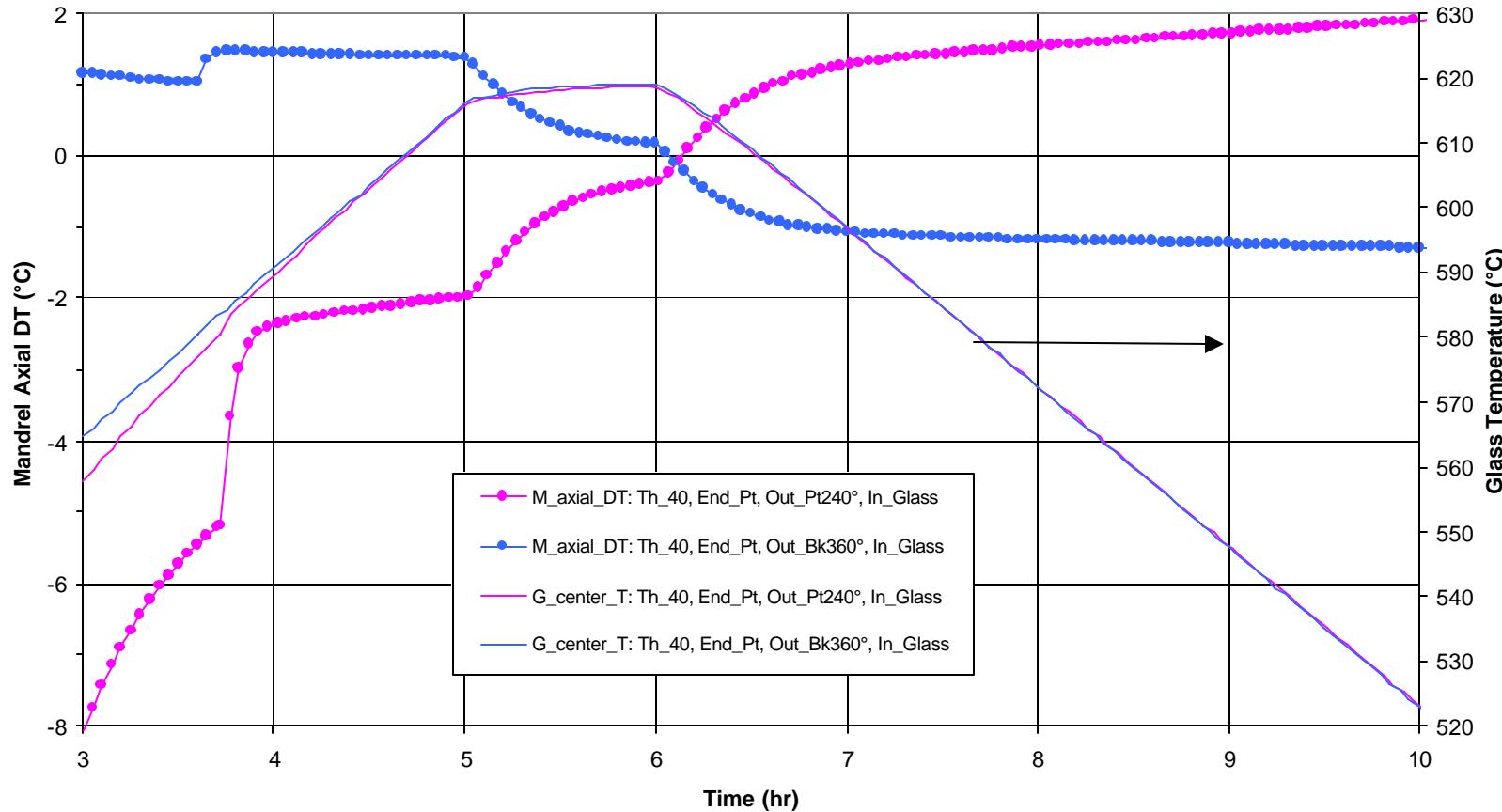
**SWALES**  
AEROSPACE



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for inside Bare Glass, = -0.3 °C for inside Black  
 $\Rightarrow$  Coating mandrel inside black reduces glass circum DT by 0.3 °C.

# Effect of Coating Mandrel Outside Black on Mandrel Axial DT

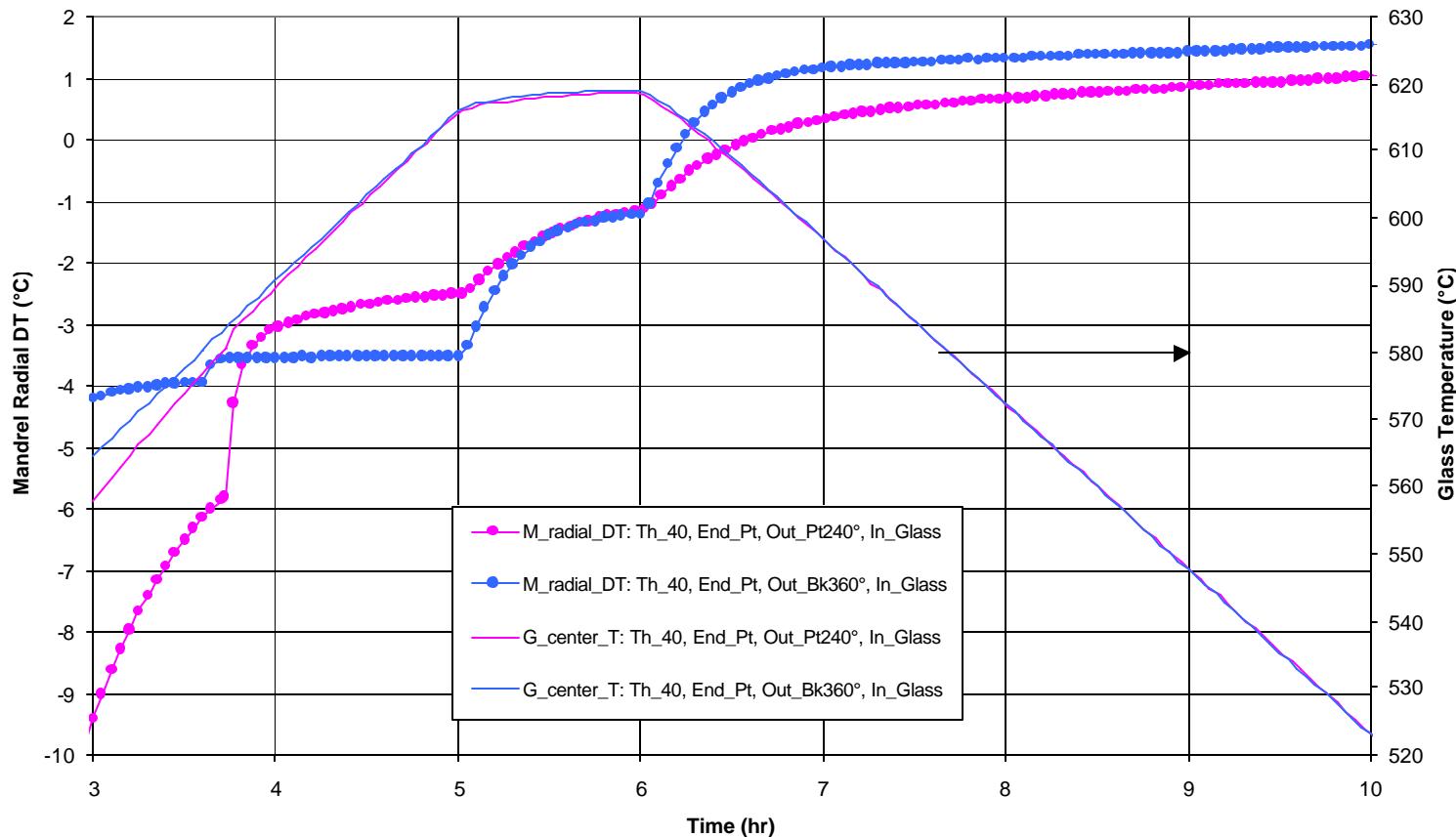


Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Axial DT = -2.3 °C for outside 240° Pt, = 1.5 °C for outside Black  
⇒ Coating mandrel outside black reduces axial DT by 0.9 °C.

# Effect of Coating Mandrel Outside Black on Mandrel Radial DT

**SWALES**  
AEROSPACE

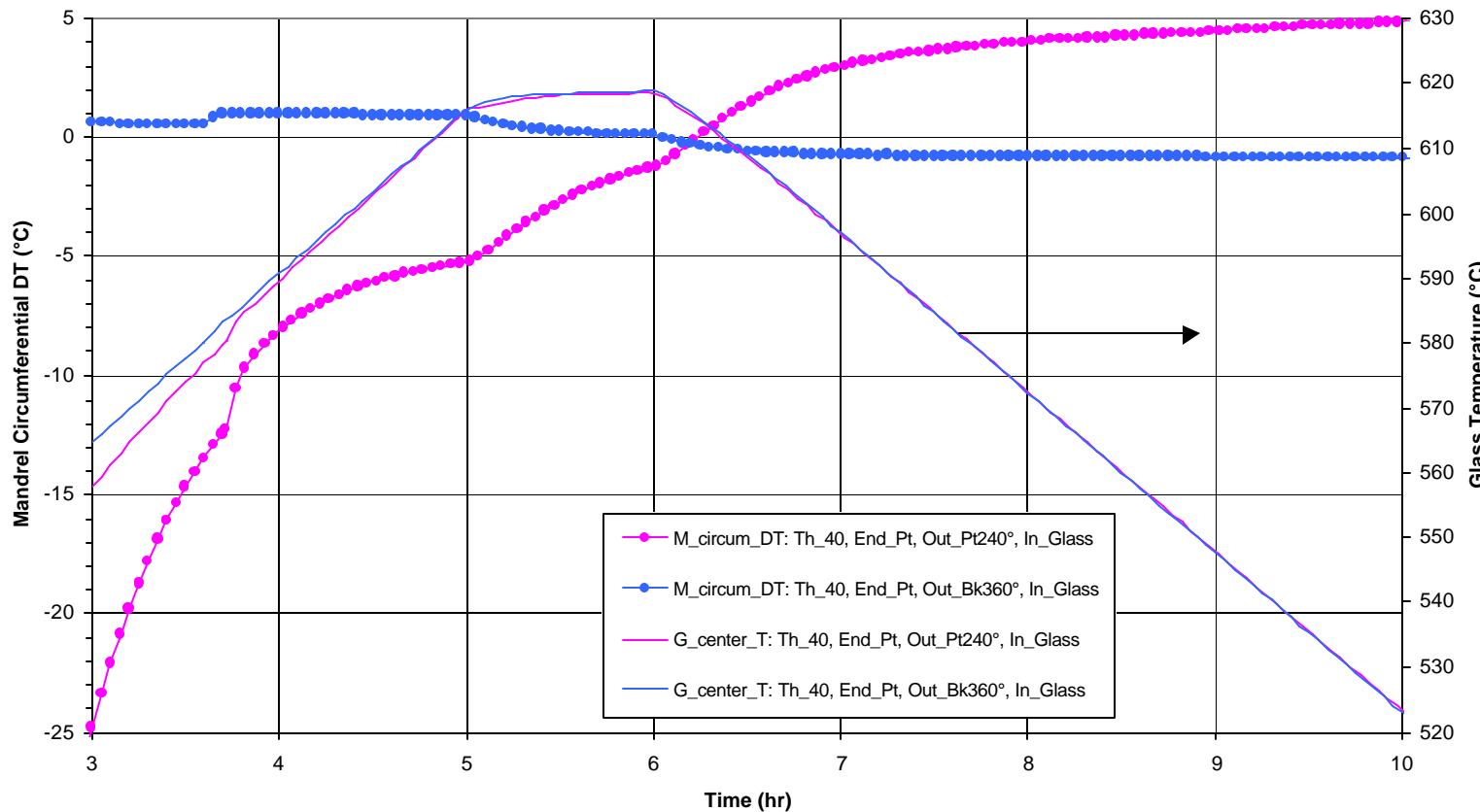


Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Radial DT =  $-3.0\text{ }^{\circ}\text{C}$  for outside  $240^{\circ}$  Pt, =  $-3.5\text{ }^{\circ}\text{C}$  for outside Black  
 $\Rightarrow$  Coating mandrel outside black increases radial DT by  $0.5\text{ }^{\circ}\text{C}$ .

Contrary to the trend, coating mandrel outside black increases radial DT.

# Effect of Coating Mandrel Outside Black on Mandrel Circum DT

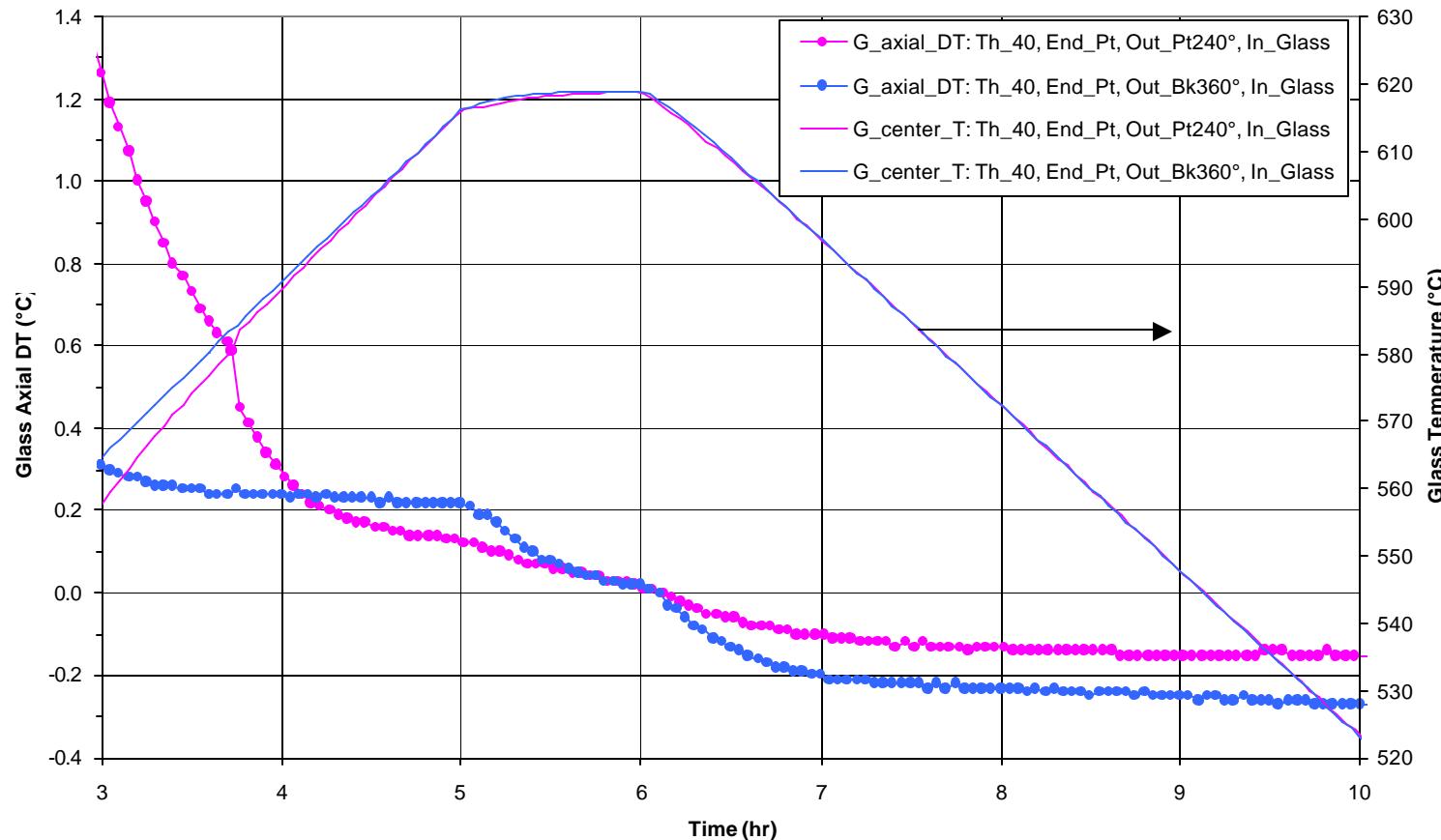


Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location: 45° to 0°

Glass Center = 590 °C, Mandrel Circum DT = -8.0 °C for outside 240° Pt, = 1.0 °C for outside Black  
⇒ Coating mandrel outside black reduces circum DT by 7.0 °C.

Coating mandrel outside black reduces axial & circum DT because high emissivity coating increases the radiative heating. This speeds up the equilibrating process.

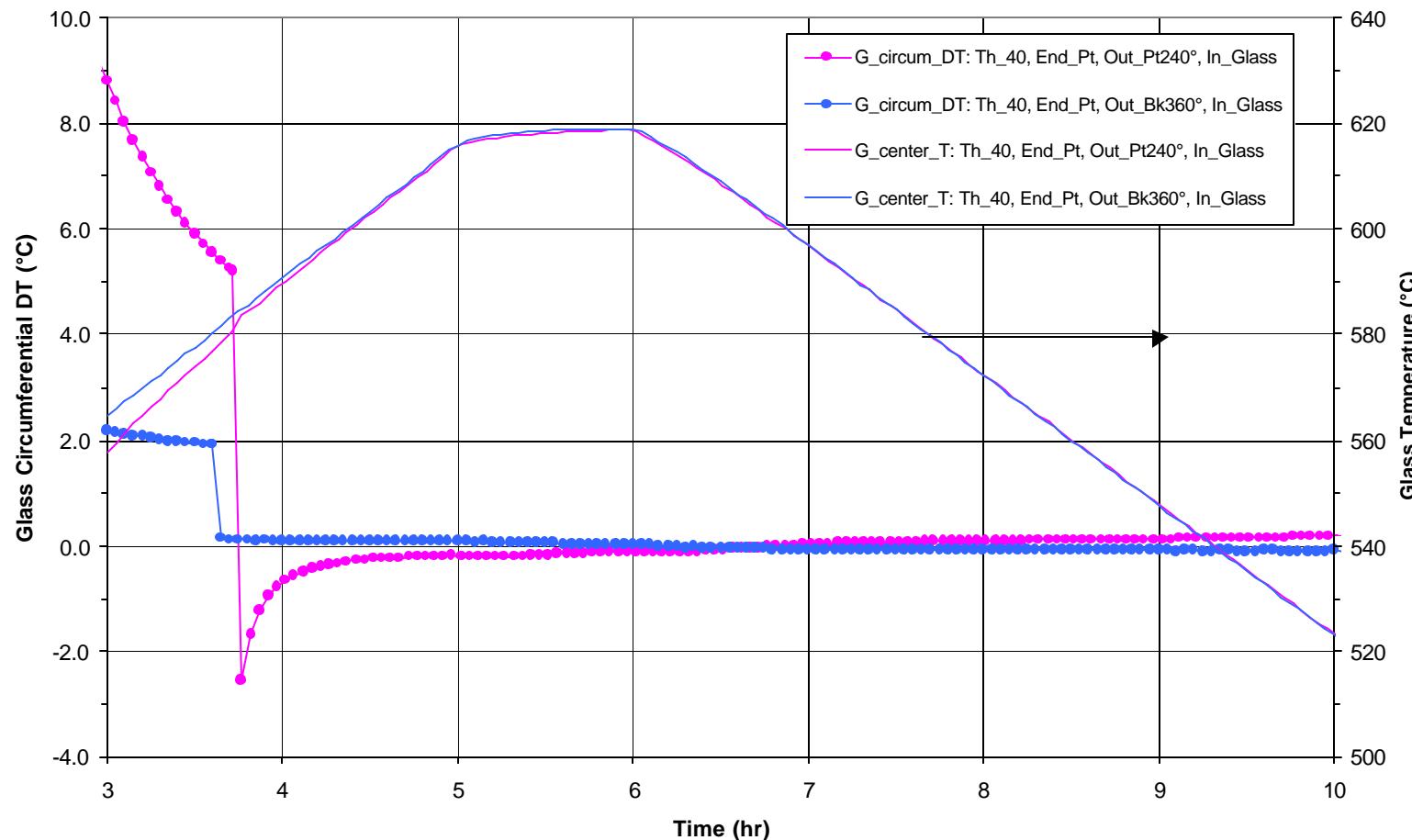
# Effect of Coating Mandrel Outside Black on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.28 °C for outside 240° Pt,      = 0.24 °C for outside Black  
 ⇒ Coating mandrel outside black reduces glass axial DT slightly.

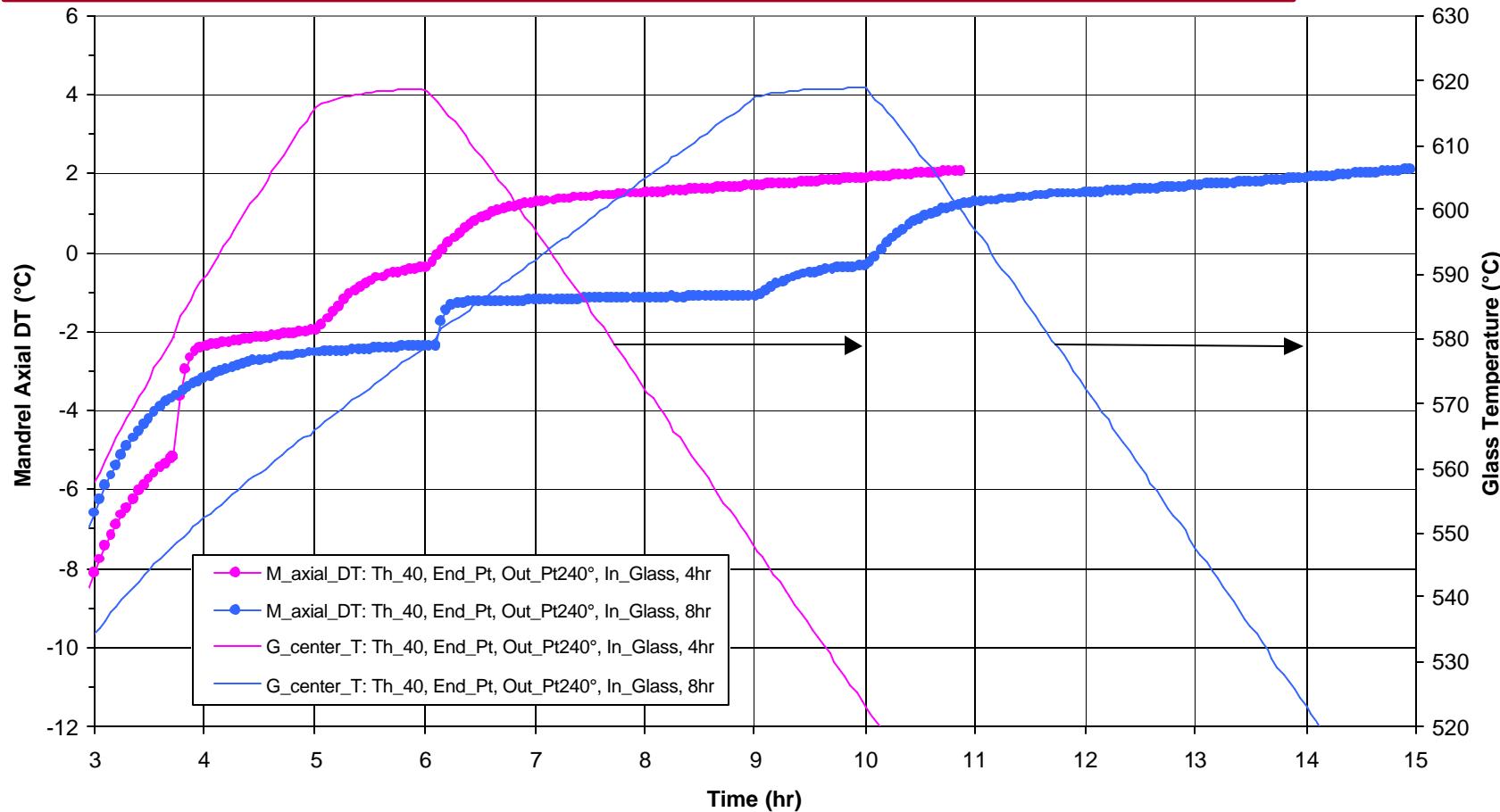
# Effect of Coating Mandrel Outside Black on Glass Circum DT



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for outside 240° Pt,  
= 0.1 °C for outside Black  
⇒ Coating mandrel outside black reduces glass circum DT by 0.6 °C.

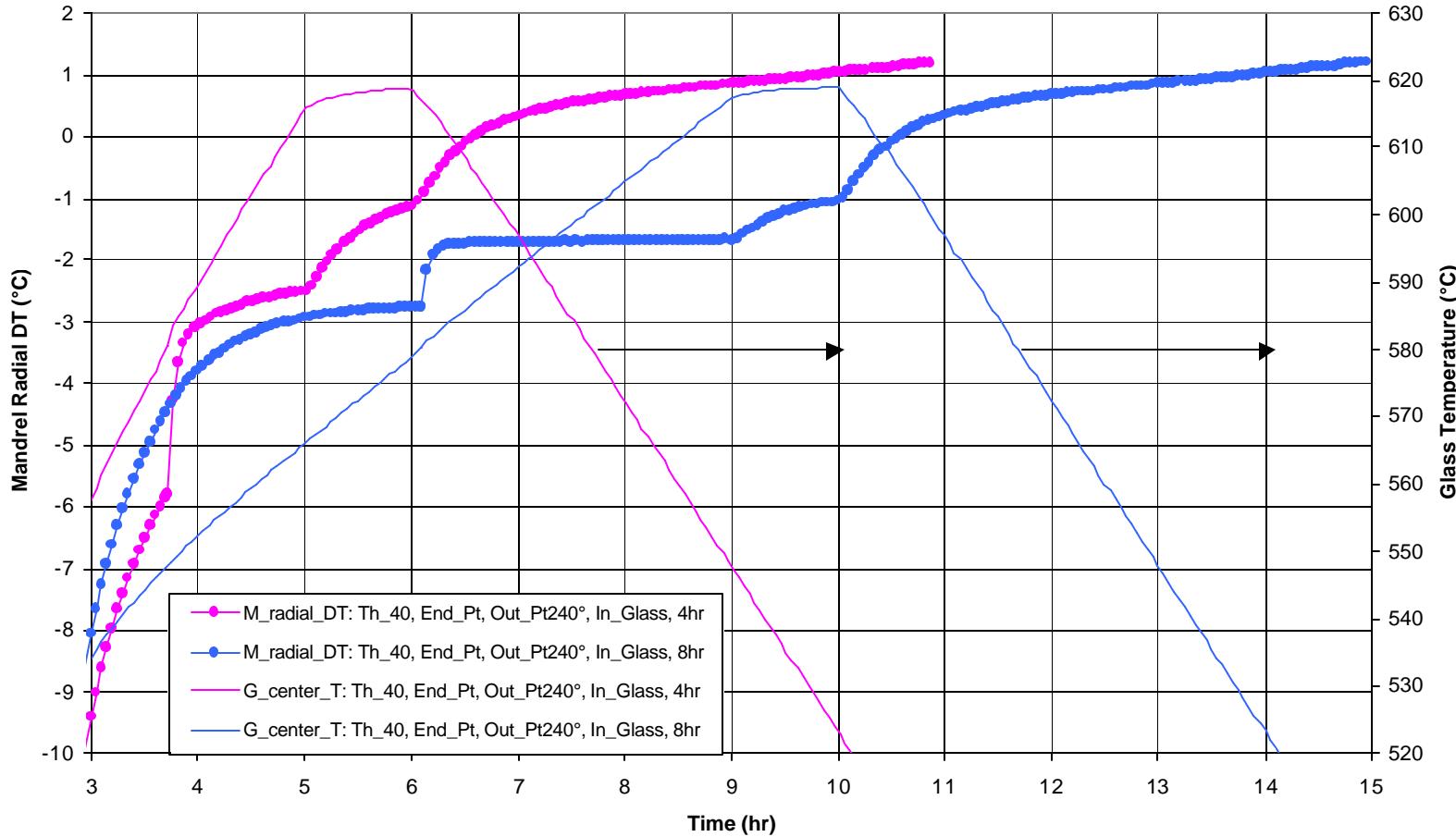
# Effect of Long Ramp Up on Mandrel Axial DT



Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Axial DT = -2.3 °C for 4 hr Ramp Up, = -1.2 °C for 8 hr Ramp Up  
 ⇒ Long warm up reduces axial DT by 1.1 °C.

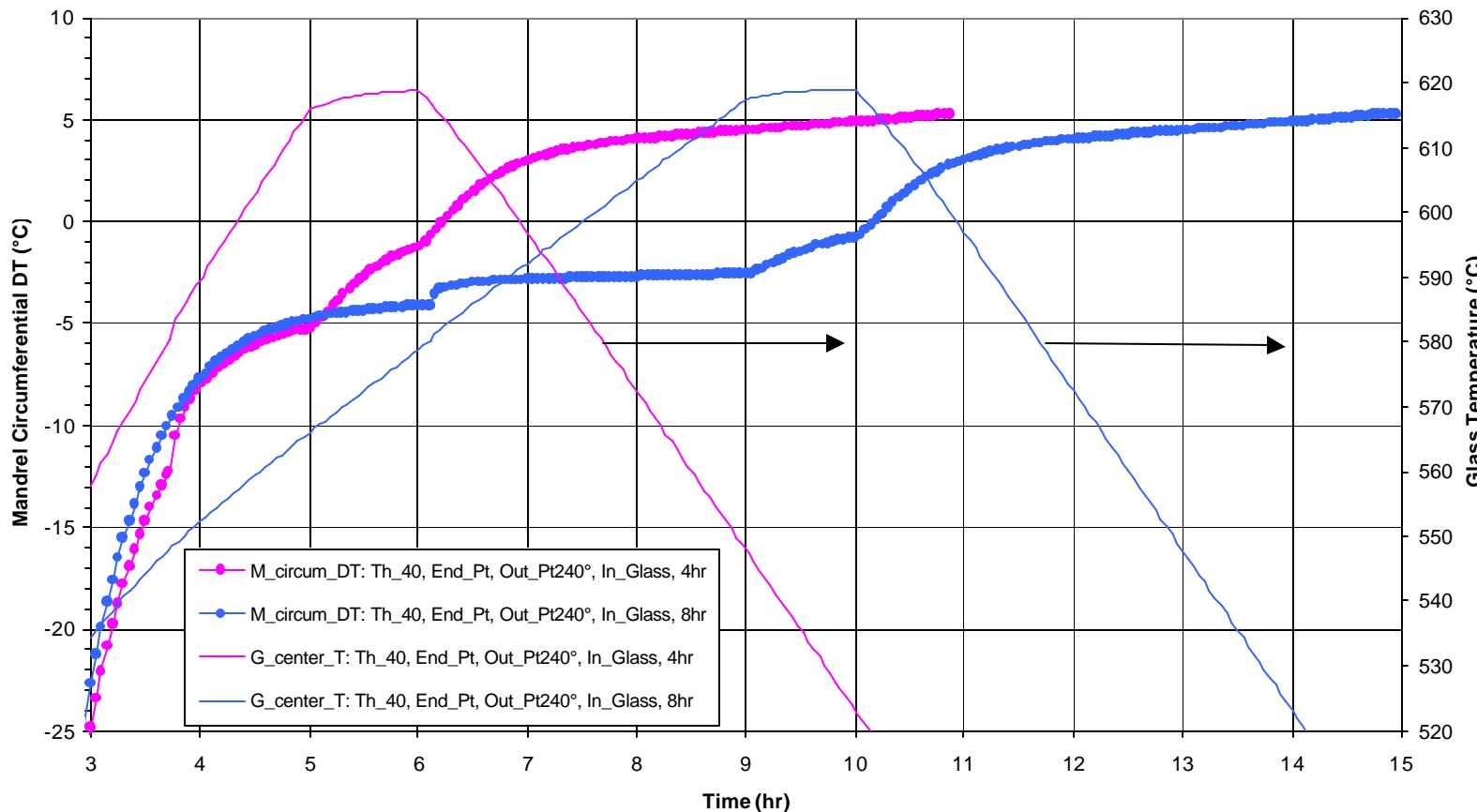
# Effect of Long Ramp Up on Mandrel Radial DT



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Radial DT = -3.0 °C for 4 hr Ramp Up, = -1.7 °C for 8 hr Ramp Up  
 ⇒ Long warm up reduces radial DT by 1.3 °C.

# Effect of Long Ramp Up on Mandrel Circum DT

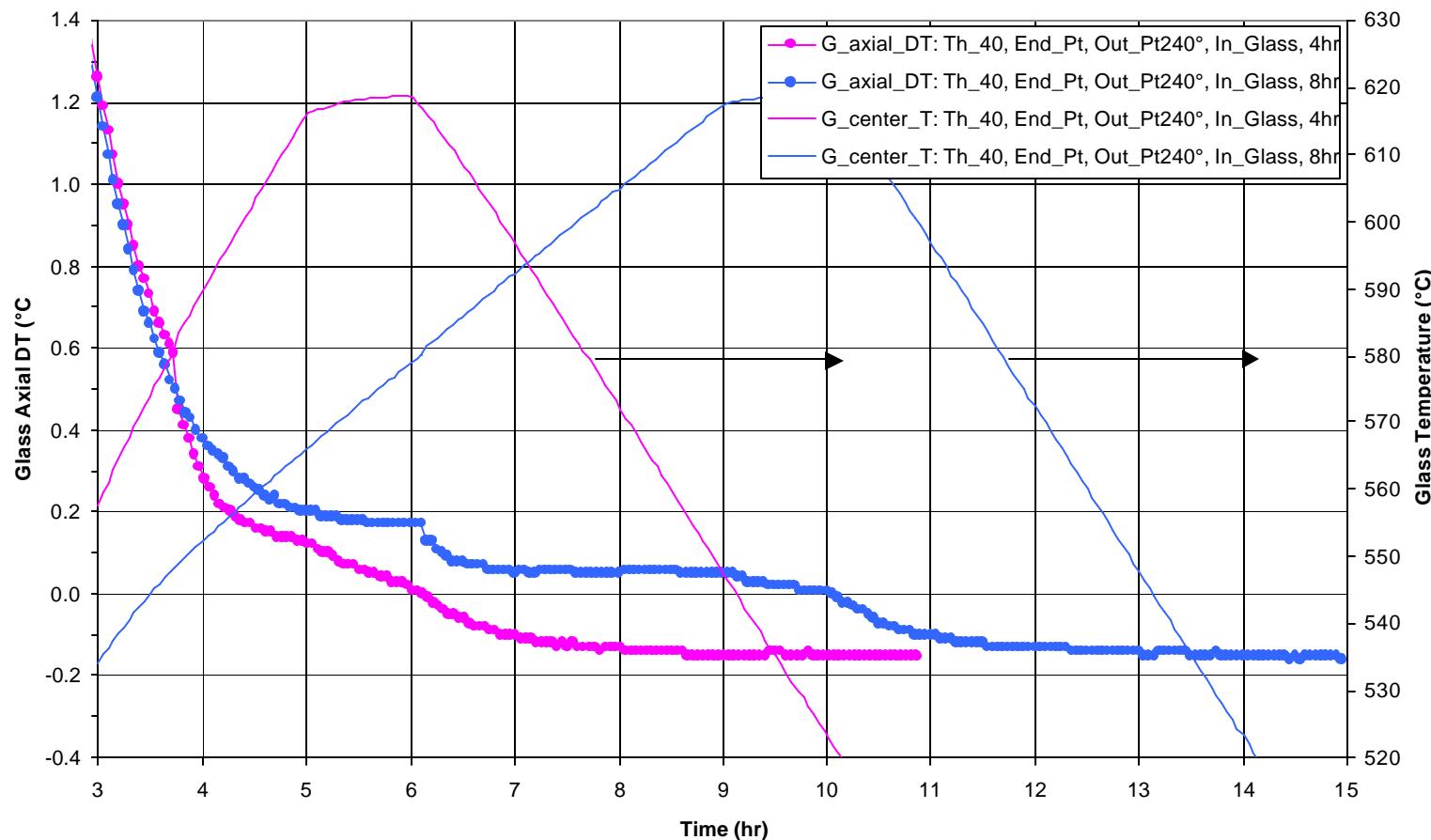


Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location: 45° to 0°

Glass Center = 590 °C, Mandrel Circum DT = -8.0 °C for 4 hr Ramp Up, = -2.9 °C for 8 hr Ramp Up  
 ⇒ Long warm up reduces circum DT by 5.1 °C.

Long warm up reduces all DT's. The longer the warm up time, the more time the mandrel has to equilibrate to the temperature change.

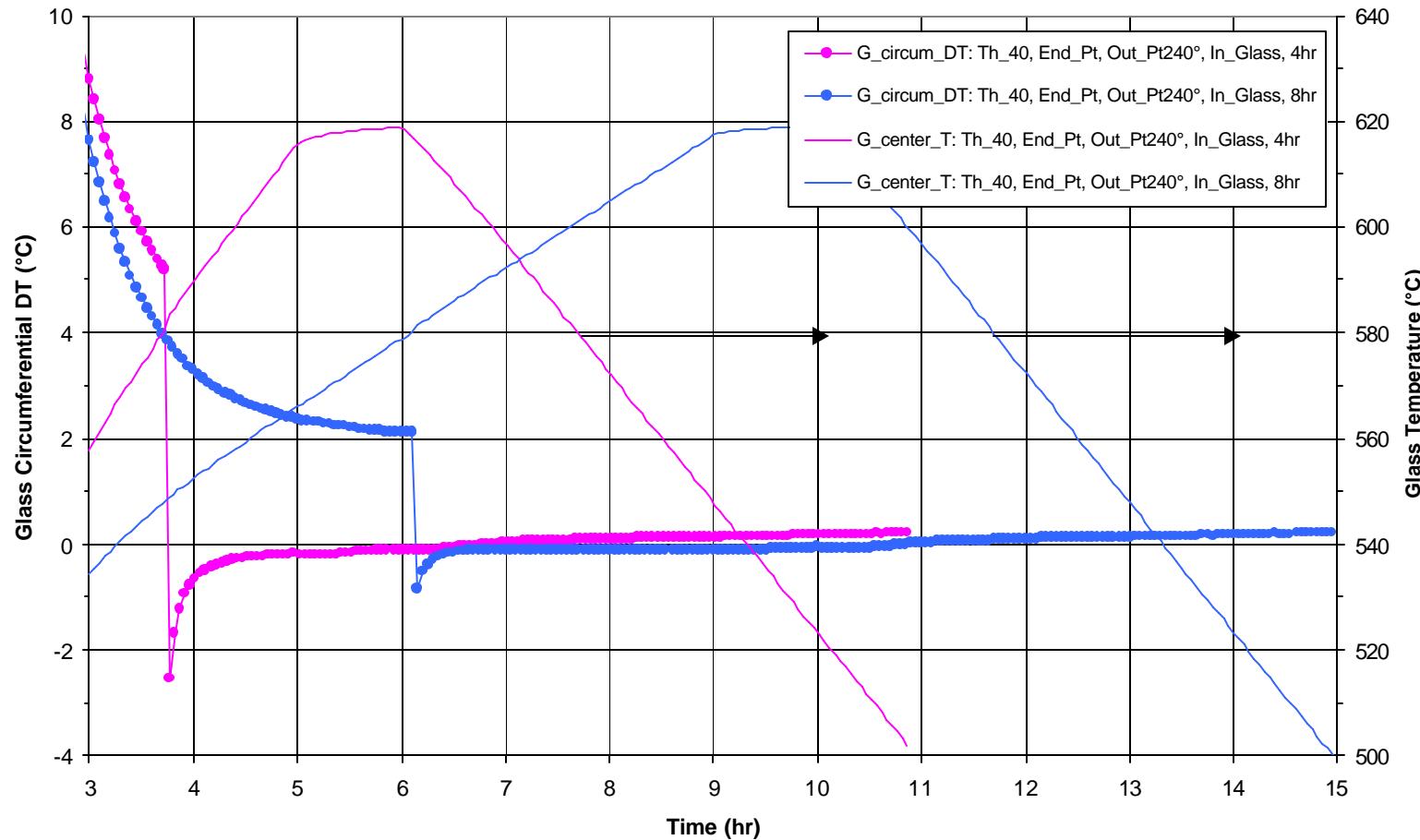
# Effect of Long Ramp Up on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.28 °C for 4 hr Ramp Up,      = 0.06 °C for 8 hr Ramp Up  
 ⇒ Long warm up reduces glass axial DT by 0.2 °C.

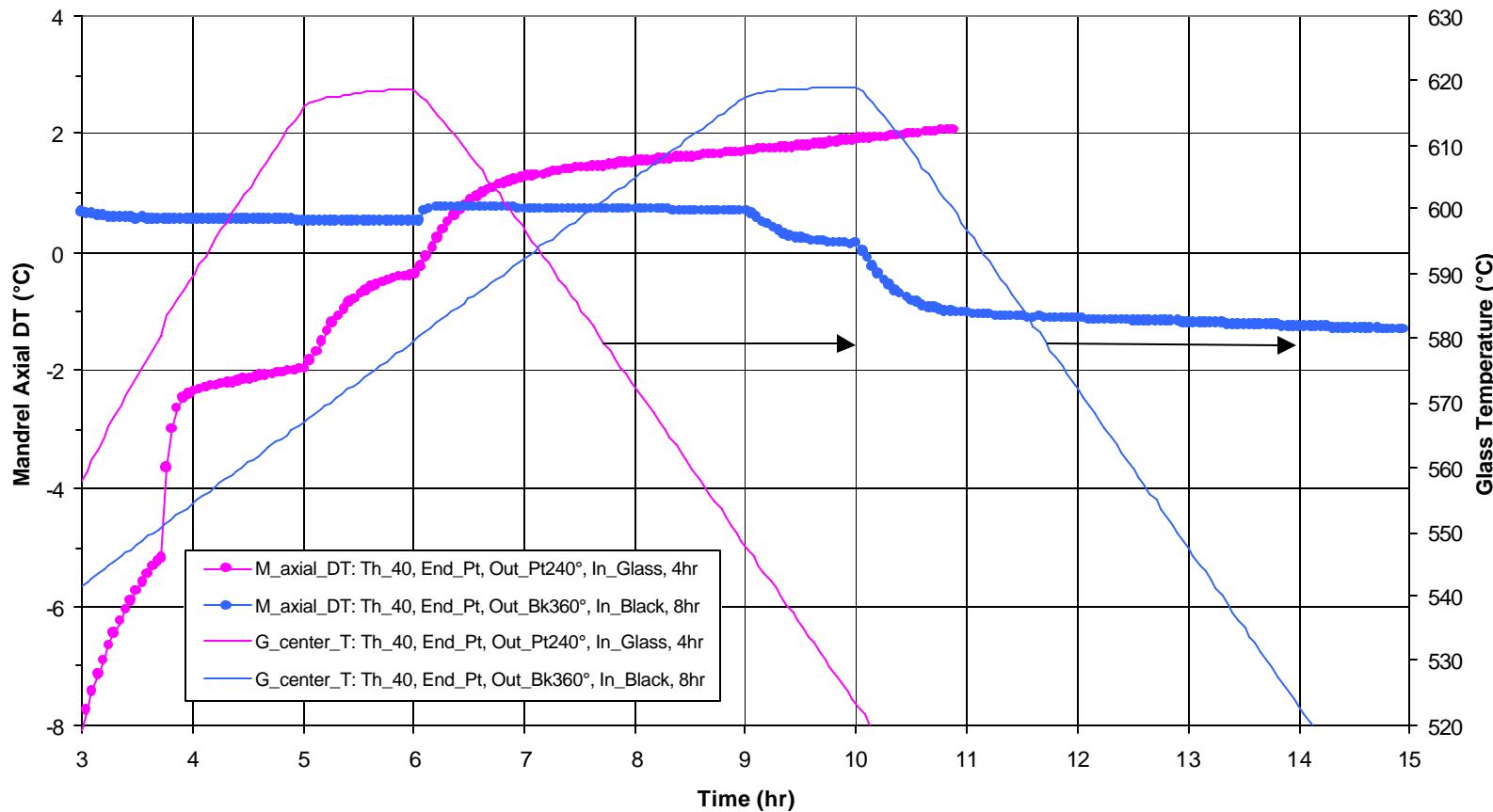
# Effect of Long Ramp Up on Glass Circum DT



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for 4 hr Ramp Up,      = -0.1 °C for 8 hr Ramp Up  
 ⇒ Long Warm up reduces glass circum DT by 0.5 °C.

# Effect of Best Coatings & Long Ramp Up on Mandrel Axial DT

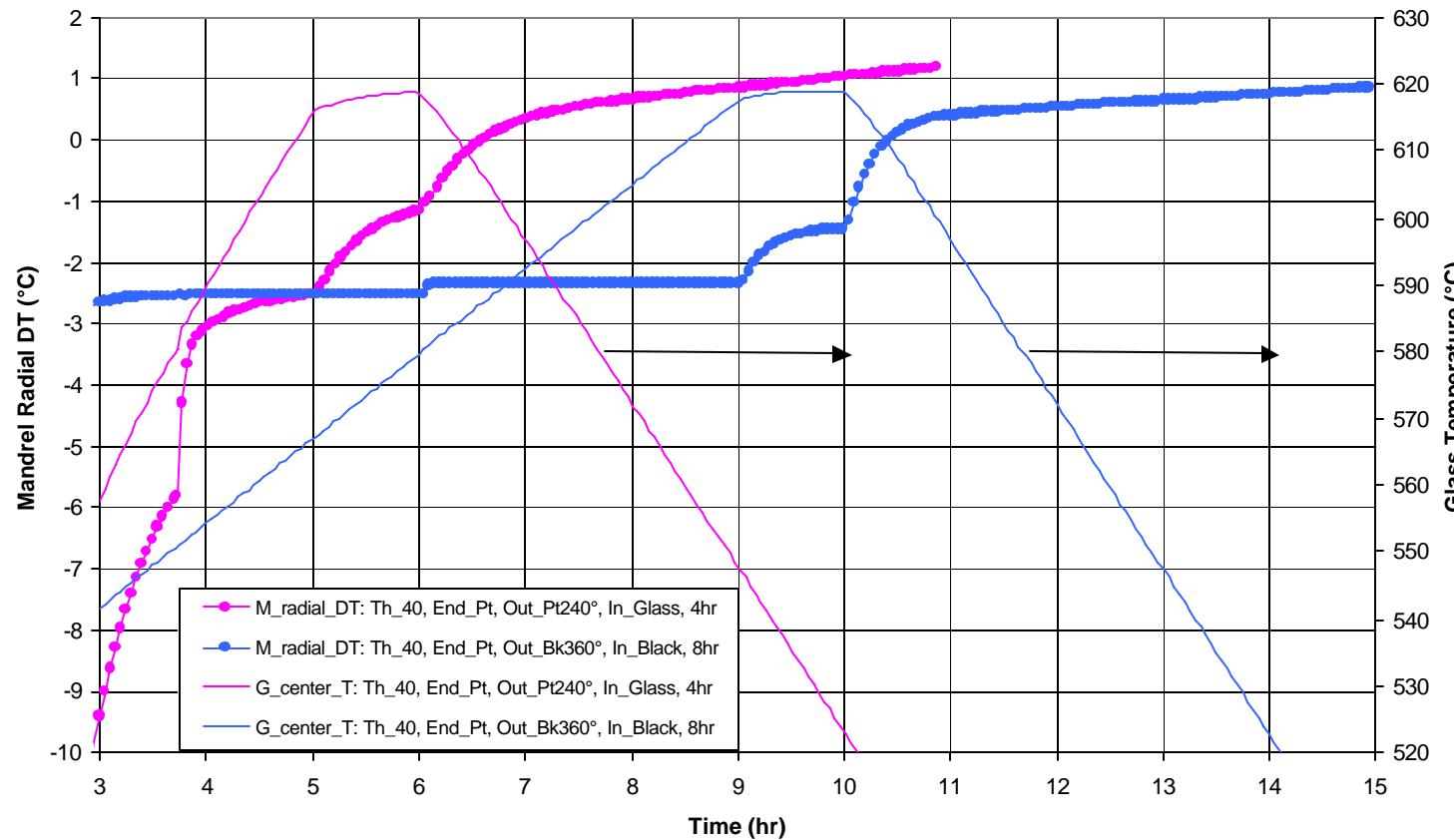


Mandrel Axial Location: Aft to Center, Radial Location: Outer Surface, Circumferential Location: Top (0°)

Glass Center = 590 °C, Mandrel Axial DT = -2.3 °C for 4 hr Ramp Up, = 0.8 °C for Best Coatings & 8 hr Ramp Up  
 ⇒ Best coatings & long warm up reduces axial DT by 1.5 °C.

# Effect of Best Coatings & Long Ramp Up on Mandrel Radial DT

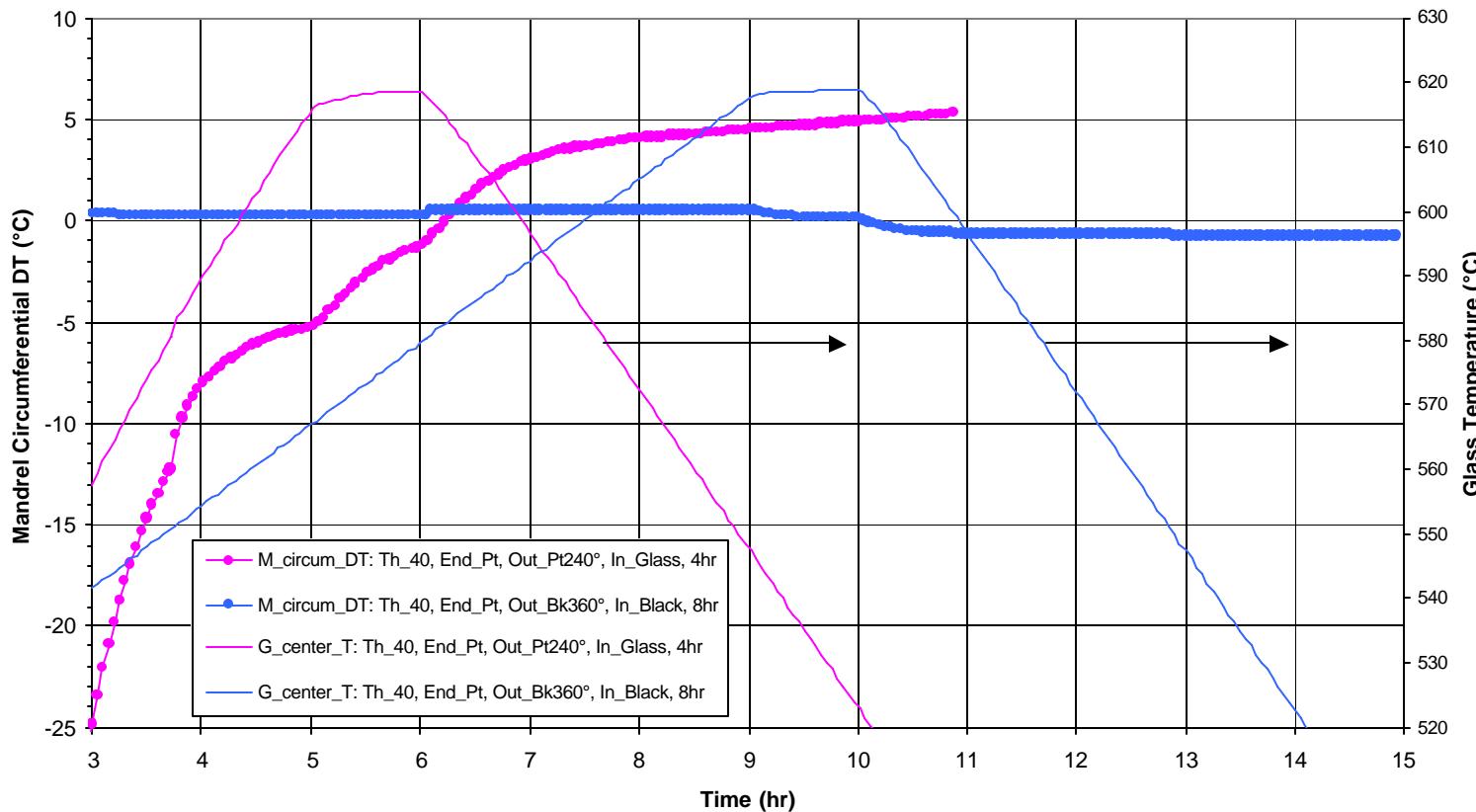
**SWALES**  
AEROSPACE



Mandrel Axial Location: Center, Radial Location: Mid to Outer Surface, Circumferential Location: Top ( $0^{\circ}$ )

Glass Center =  $590\text{ }^{\circ}\text{C}$ , Mandrel Radial DT =  $-3.0\text{ }^{\circ}\text{C}$  for 4 hr Ramp Up, =  $-2.3\text{ }^{\circ}\text{C}$  for Best Coatings & 8 hr Ramp Up  
⇒ Best coatings & long warm up reduces radial DT by  $0.7\text{ }^{\circ}\text{C}$ .

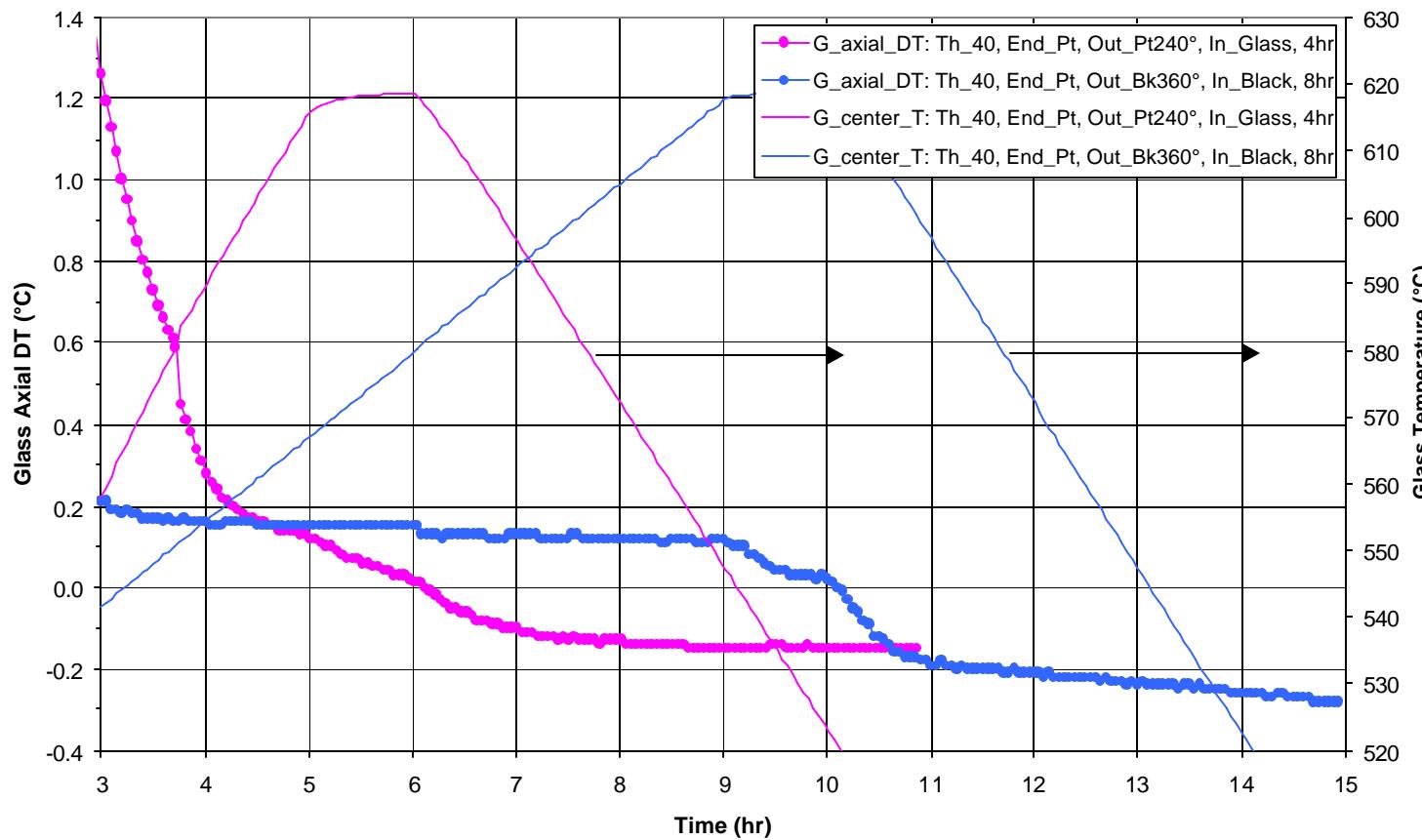
# Effect of Best Coatings & Long Ramp Up on Mandrel Circum DT



Mandrel Axial Location: Center, Radial Location: Outer Surface, Circumferential Location:  $45^{\circ}$  to  $0^{\circ}$

Glass Center =  $590^{\circ}\text{C}$ , Mandrel Circum DT =  $-8.0^{\circ}\text{C}$  for 4 hr Ramp Up, =  $0.6^{\circ}\text{C}$  for Best Coatings & 8 hr Ramp Up  
⇒ Best coatings & long warm up reduces circum DT by  $7.4^{\circ}\text{C}$ .

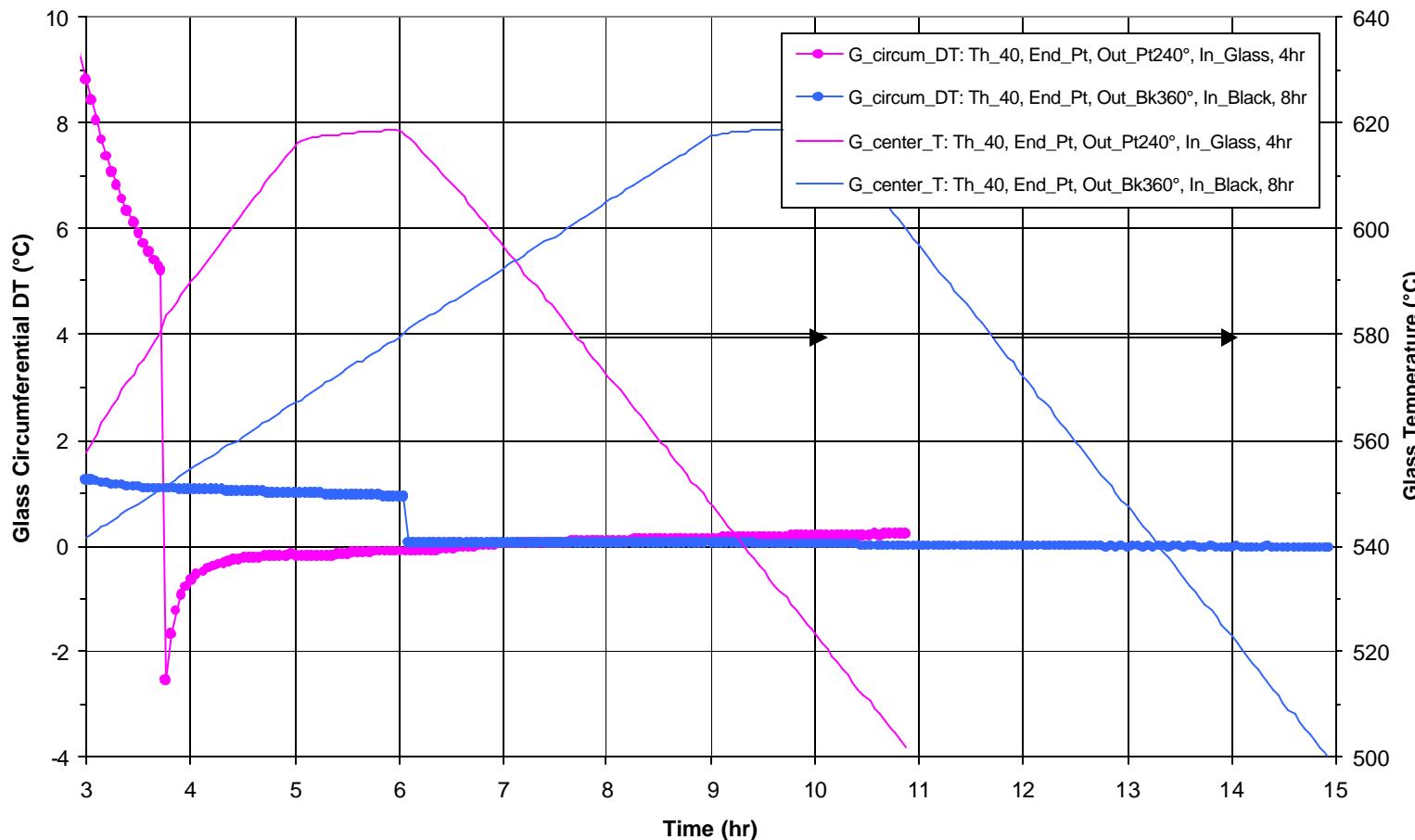
# Effect of Best Coatings & Long Ramp Up on Glass Axial DT



Glass Axial Location: Aft Edge to Center, Circumferential Location: Center

Glass Center = 590 °C, Glass Axial DT = 0.28 °C for 4 hr Ramp Up, = 0.12 °C for Best Coatings & 8 hr Ramp Up  
⇒ Best coatings & long warm up reduces glass axial DT by 0.16 °C.

# Effect of Best Coatings & Long Ramp Up on Glass Circum DT



Glass Axial Location: Center, Circumferential Location: Right Edge to Center

Glass Center = 590 °C, Glass Circum DT = -0.7 °C for 4 hr Ramp Up, = -0.1 °C for Best Coatings & 8 hr Ramp Up  
 ⇒ Best coatings & long warm up reduces glass circum DT by 0.6 °C.

# Reduction of Temperature Difference at Glass Slumping

Reduction of Temperature Difference at time of Glass Center = 590 °C

Magnitude of DT are compared. All comparisons with respect to baseline case.

Positive value indicates improvement. Negative value indicates change is worse.

Case Description	Baseline	Original	30 in thick	20 in thick	Pt 360° Out
Filename	t40_ept_opt240_igl	t40_egl_opt240_igl	t30_ept_opt240_igl	t20_ept_opt240_igl	t40_ept_opt360_igl
Thickness (mm)	40	40	30	20	40
Ends Optics	Pt Coated	Bare Surface	Pt Coated	Pt Coated	Pt Coated
Outside Surface Optics	240° Pt	240° Pt	240° Pt	240° Pt	360° Pt
Inside Surface Optics	Bare Surface				
Ramp Up time (hr)	4	4	4	4	4
Mandrel Axial DT	(-2.34 Ref Temp)	-1.32	0.41	0.81	0.10
Mandrel Radial DT	(-3.03 Ref Temp)	0.06	1.30	2.07	-1.53
Mandrel Circum DT	(-7.99 Ref Temp)	0.38	3.62	5.40	-1.89
Glass Axial DT	(0.28 Ref Temp)	-0.56	0.17	0.23	-0.27
Glass Circum DT	(-0.65 Ref Temp)	0.07	0.45	0.60	-0.28
Simple Sum ( Mandrel DT )		<b>-0.88</b>	<b>5.33</b>	<b>8.28</b>	<b>-3.32</b>

Case Description	Baseline	Black Inside	Black Outside	8 hr Ramp Up	Best Coatings & 8 hr Ramp Up
Filename	t40_ept_opt240_igl	t40_ept_opt240_ibk	t40_ept_obk360_igl	t40_ept_opt240_igl_8hr	t40_ept_obk360_ibk_8hr
Thickness (mm)	40	40	40	40	40
Ends Optics	Pt Coated	Pt Coated	Pt Coated	Pt Coated	Pt Coated
Outside Surface Optics	240° Pt	240° Pt	360° Black	240° Pt	360° Black
Inside Surface Optics	Bare Surface	Black Paint	Bare Surface	Bare Surface	Black Paint
Ramp Up time (hr)	4	4	4	8	8
Mandrel Axial DT	(-2.34 Ref Temp)	0.27	0.89	1.13	1.58
Mandrel Radial DT	(-3.03 Ref Temp)	0.53	-0.51	1.31	0.70
Mandrel Circum DT	(-7.99 Ref Temp)	2.05	6.98	5.12	7.44
Glass Axial DT	(0.28 Ref Temp)	0.01	0.04	0.22	0.16
Glass Circum DT	(-0.65 Ref Temp)	0.31	0.55	0.54	0.60
Simple Sum ( Mandrel DT )		<b>2.85</b>	<b>7.36</b>	<b>7.56</b>	<b>9.72</b>

# Attachment B

## Forming Mandrels Structural Analysis

# Recommendations

## ◆ Mandrel Wall Thickness

- ❖ 30 mm wall is recommended
  - 30 mm & 20 mm walls produced less local slope changes than 40mm's
  - When gravity along is considered, 30 mm wall yields much less sag than 20 mm for Secondary Mandrel, which was not thermally analyzed.

## ◆ Temperature Uniformity

- ❖ Optimize temperature uniformity on the mandrel
  - Mandrel distortion is very sensitive to temperature gradient
    - Through thickness
    - Along axial
    - Azimuth
  - Bulk temperature change yields no distortion
  - A range of 5 to 12 arc sec. distortion was observed based on various configurations
  - Further improvement is possible.

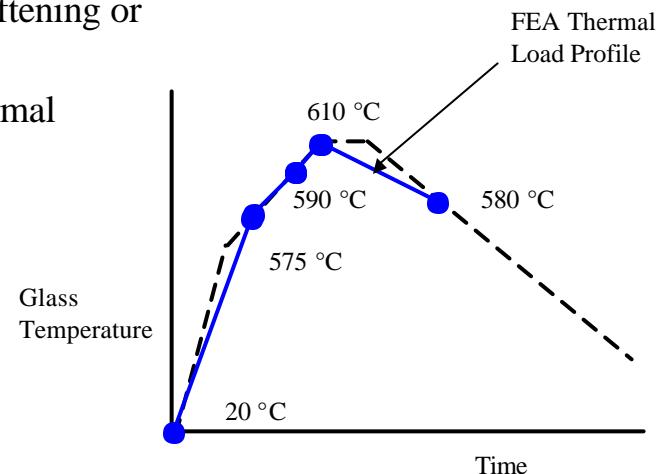
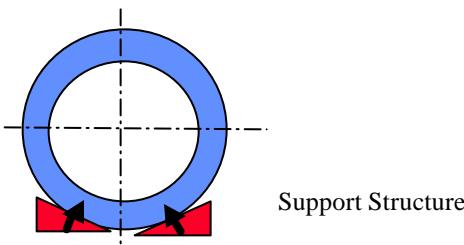
# Summary (1/2)

- ◆ Analysis covers the gravity sag & thermal distortion
  - ❖ Thermal load (nodal temperature) was mapped from thermal analysis results at various temperature profiles
    - Warm-up @ 575 °C prior to glass conforming to mandrel
    - Warm-up @ 590 °C after glass conforming to mandrel
    - Beginning of soaking @ 615 °C
    - Cool down @ 580 °C
  - ❖ Glass is considered critical at 580 °C when it starts softening or solidifying
  - ❖ The process is streamlined between structural and thermal analysis.

- ◆ Primary mandrel was analyzed

- ◆ Support structure

- ❖ Brackets (4) support at side walls.
  - ❖ Based on the current lab setup

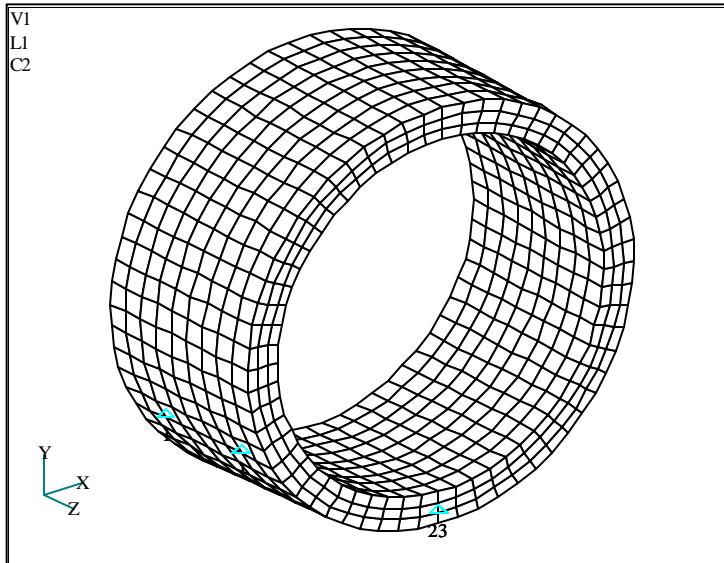


# Summary (2/2)

- ◆ We assume perfect support
  - ❖ Support structure does not have gravity sag
  - ❖ Support structure does not deform with temperature changes
  - ❖ Coeff. of friction ~ 0.4
- ◆ Effects of temperature dependent material properties vs. room temperature material properties were investigated
  - ❖ Results are conservative if room temperature material properties are employed.
- ◆ Effect of friction between mandrel and support structure during cool-down is insignificant.

# FE Model & Geometry

## Primary Forming Mandrel



### Primary Forming Mandrel Geometry

- 250mm Radius (Large End)
- Length: 300 mm
- Cone Angle: 0.42°
- 210mm Inside diameter

### FE Model

- Mandrel only
- Support structure is modeled as Gap elements assuming rigid support
- Furnace not included

### Material Properties:

- Temperature dependent

### Room Temperature Material Properties

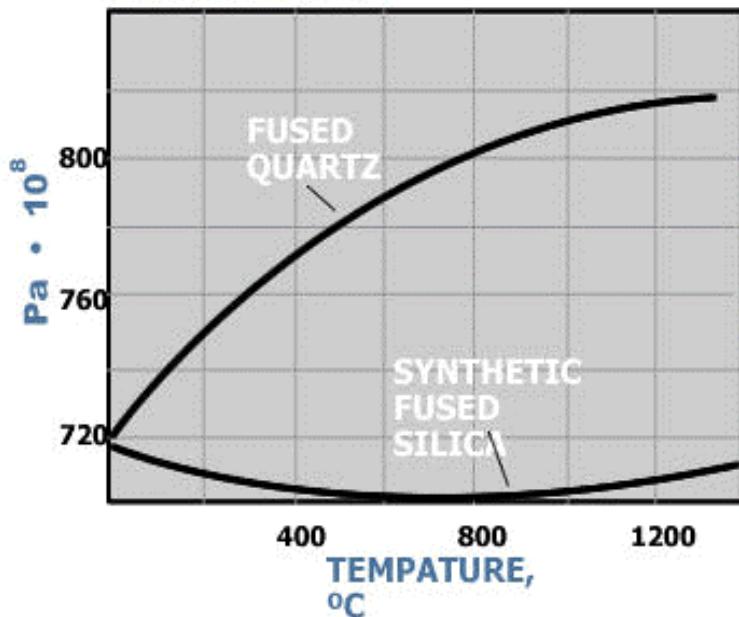
- Fused Silica SiO<sub>2</sub>
- Young's Modulus: 73.1 GPa
- Poisson's Ratio: 0.17
- Density: 2.203 gm/cc
- CTE: 0.55E-6 1/K

### Platinum Coating

- 240 ° on Outer Surface
- Both End Faces

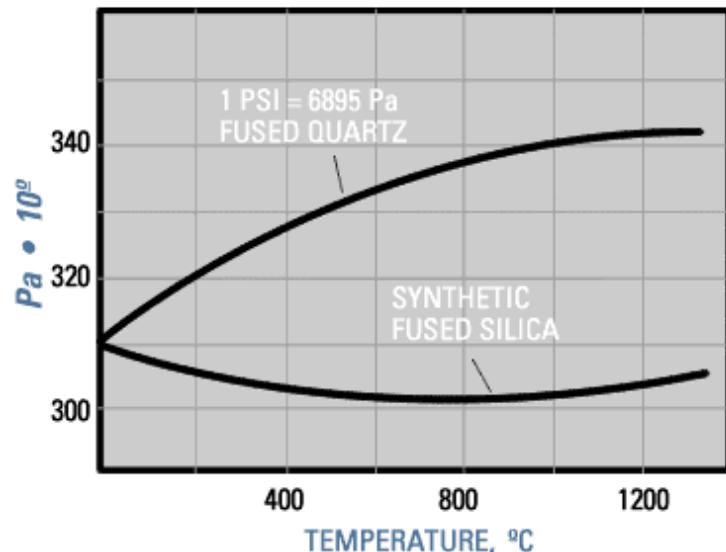
# Temperature Dependent Material Properties

## Young Modulus



Representative elastic (Young's) modulus for fused quartz.  
Source: Ibid

## Shear Modulus

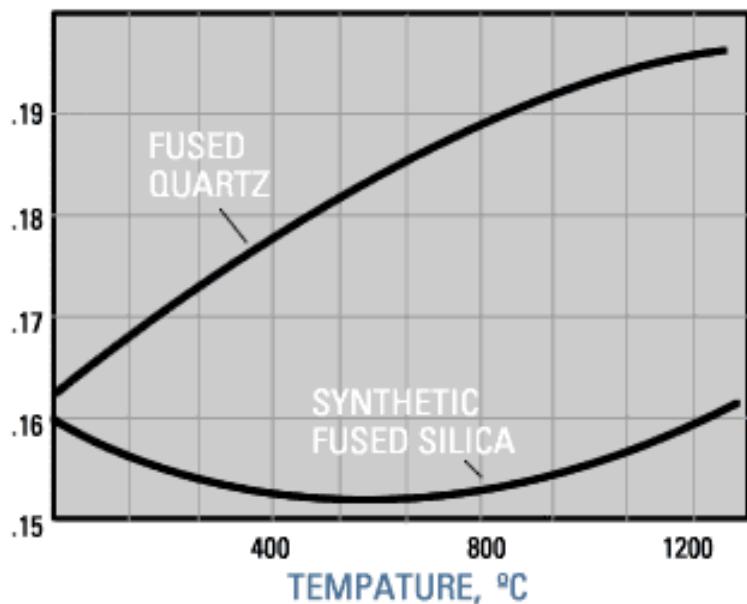


Representative shear (rigidity) modulus values for fused quartz.  
Source: National Bureau of Standards

Source: [www.gequartz.com](http://www.gequartz.com)

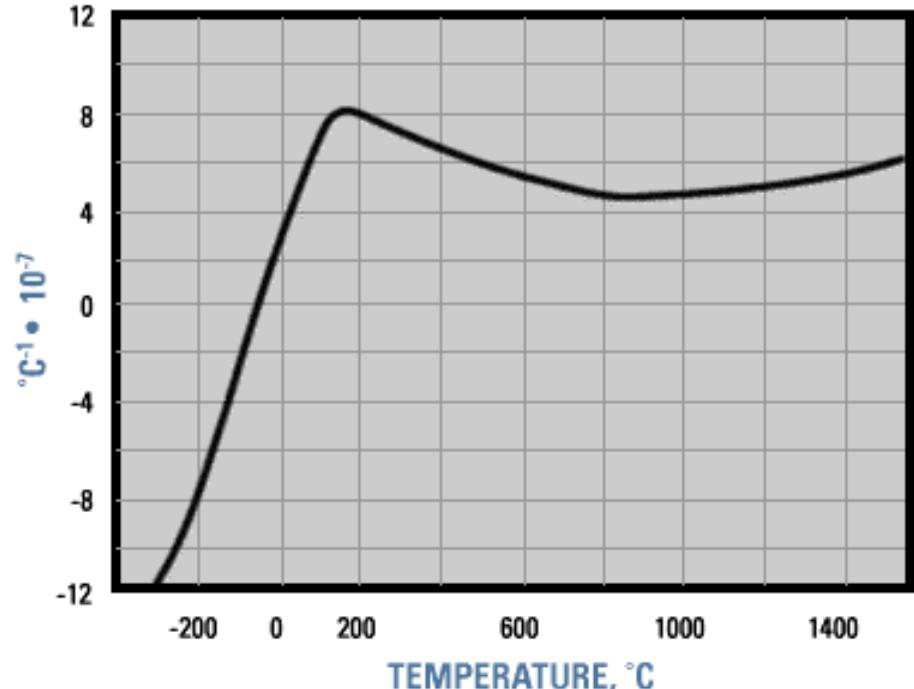
# Temperature Dependent Material Properties

*Poisson's Ratio*



Poisson's ratio for fused quartz. Source: Ibid

*Coefficient of Expansion*



Representative coefficient of expansion of fused quartz.  
Source: Published manufacturer's data.

Source: [www.gequartz.com](http://www.gequartz.com)

# Temperature Dependent Material Properties

## Function 1 – Young's Modulus

Type: vs. Temperature Num Matl: 1 Num Load: 0 Num Prop: 0

X Y

0. 72000.  
200. 75000.  
400. 77170.  
600. 78930.  
800. 80200.

## Function 3 – Possion's Ratio

Type: vs. Temperature Num Matl: 1 Num Load: 0 Num Prop: 0

X Y

0. 0.1629  
200. 0.1702  
400. 0.1779  
600. 0.1838  
800. 0.1891

## Function 2 – Shear modulus

Type: vs. Temperature Num Matl: 1 Num Load: 0 Num Prop: 0

X Y

0. 31118.  
200. 32086.  
400. 32771.  
600. 33353.  
800. 33765.

## Function 4 – Coefficient of Thermal Expansion

Type: vs. Temperature Num Matl: 1 Num Load: 0 Num Prop: 0

X Y

0. 0.000000316  
138. 0.0000008  
175. 0.000000821  
400. 0.000000666  
600. 0.000000545  
800. 0.000000473

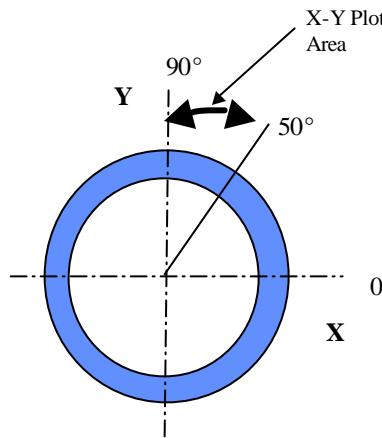
Units:

X: °C

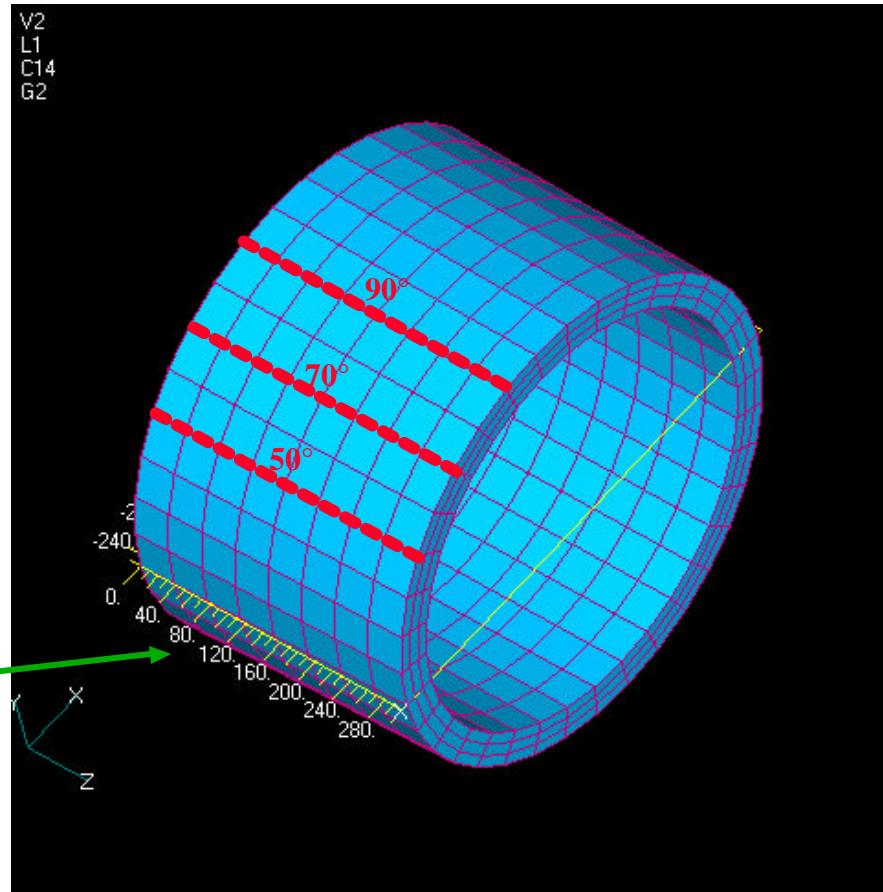
Y:

Young's Modulus & Shear modulus: Mpa  
CTE: mm/mm/°C

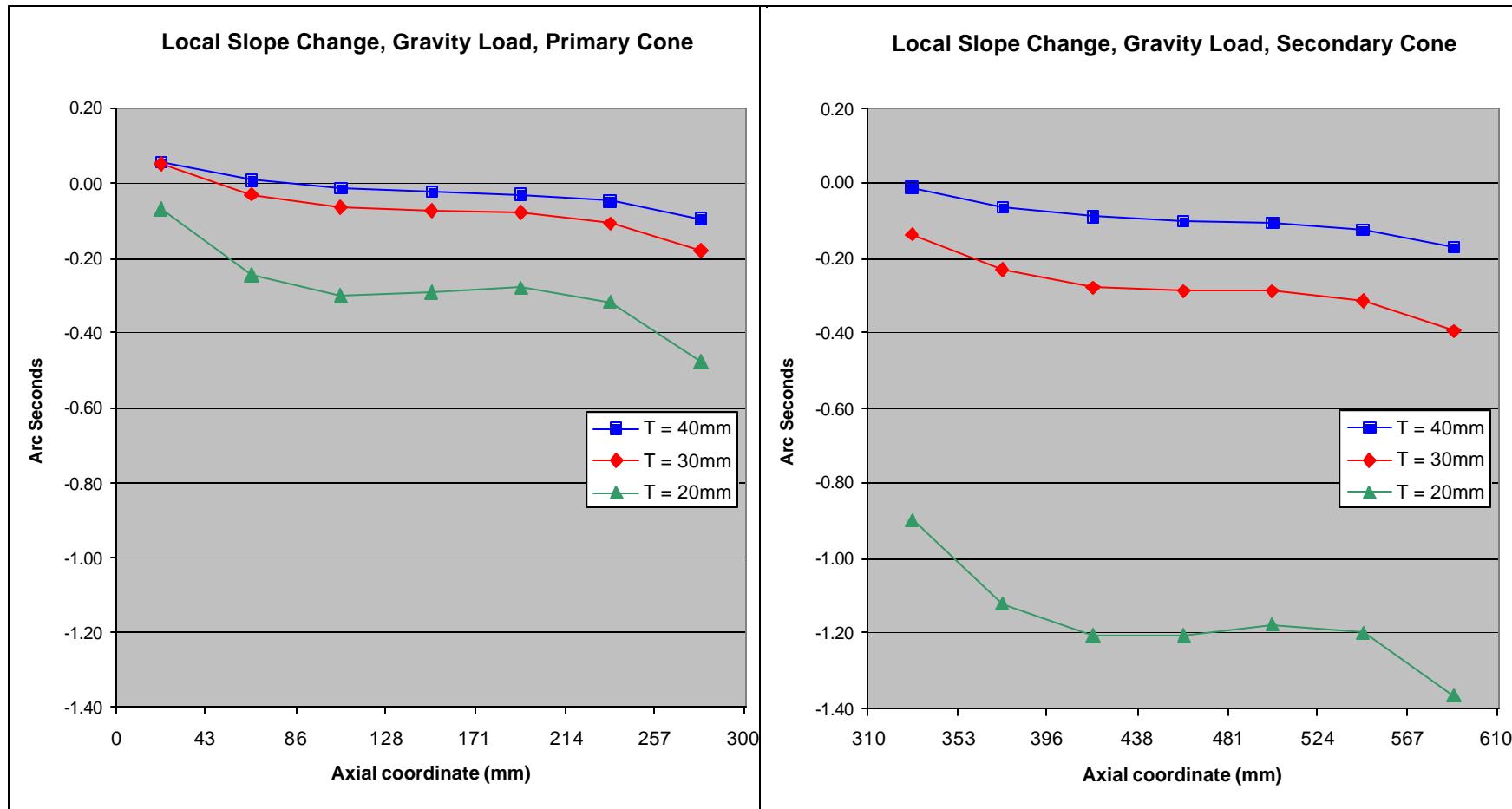
# Axial Local Slope Change X-Y Plot Locations



**Big End:** Z=0 mm  
**Small End:** Z = 300 mm



# Local Slope Change due to Gravity Sag with Various Mandrel Wall Thicknesses



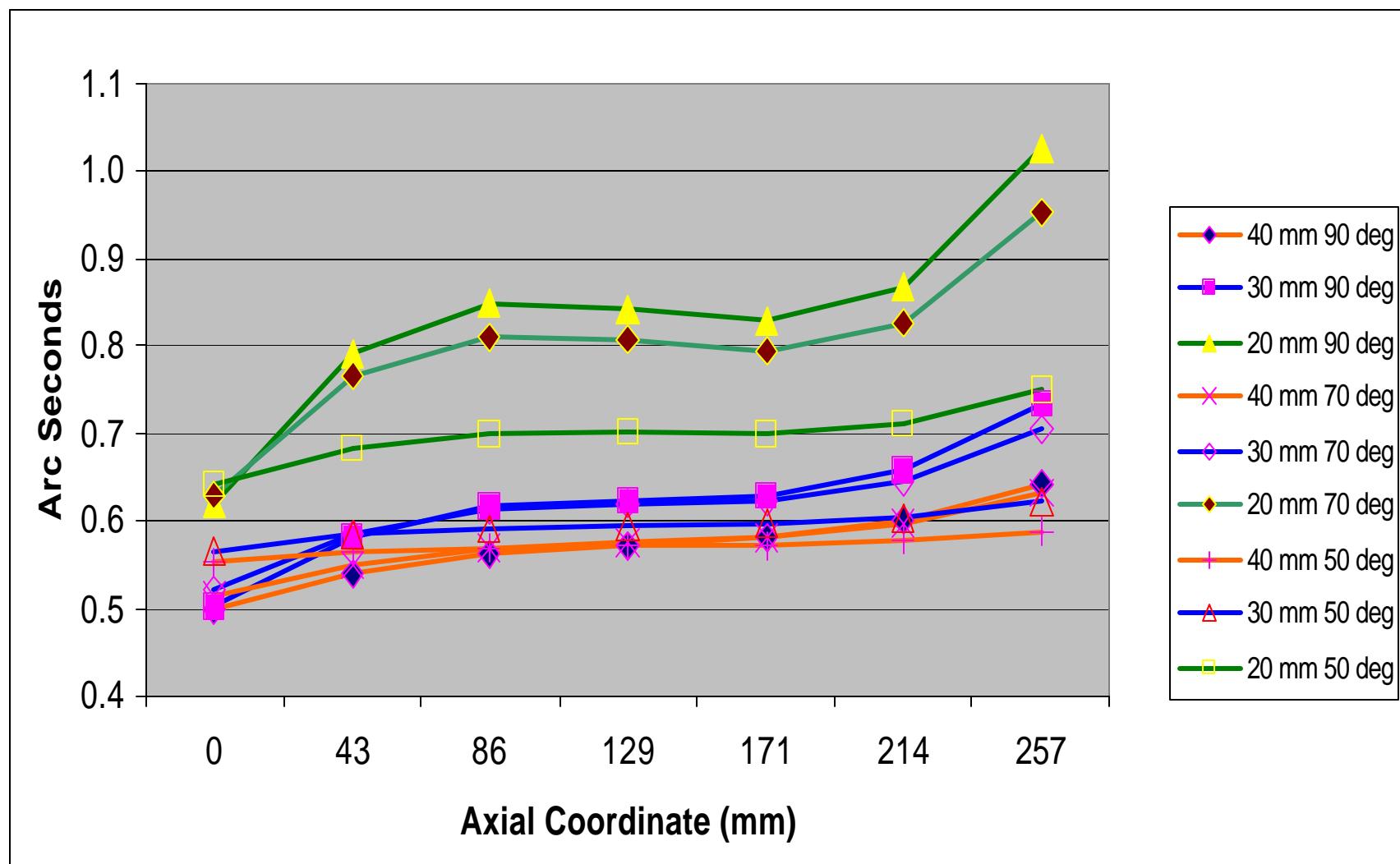
Plot points: Axial direction @ 90°

Note: Secondary mandrel was included in Sag analysis.

# Local Slope Change - Primary Mandrel

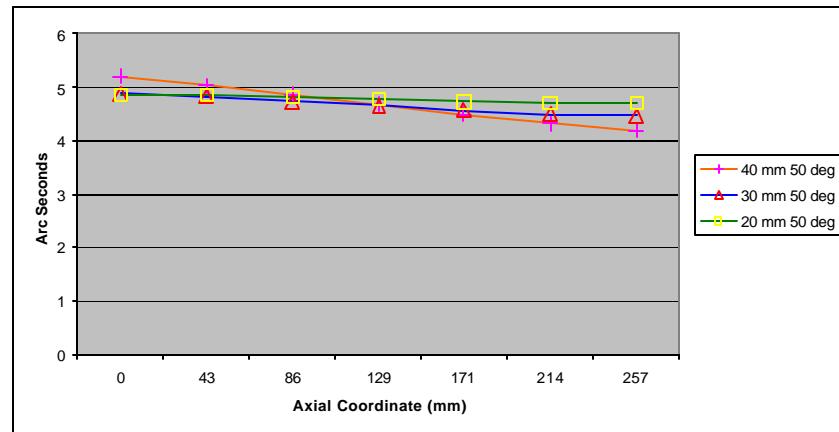
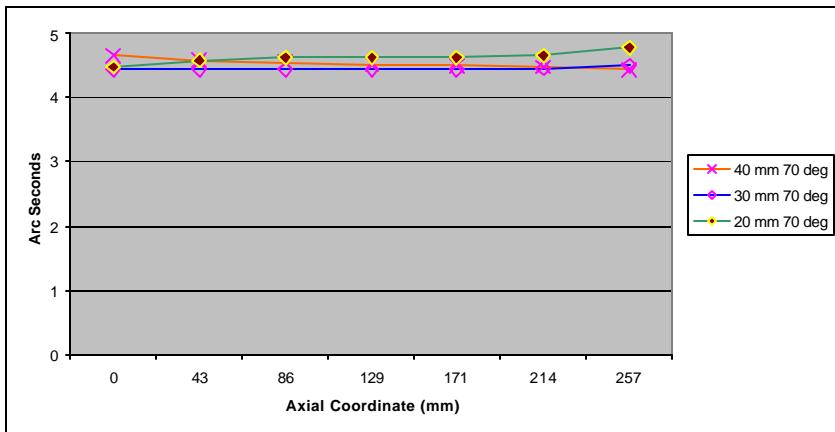
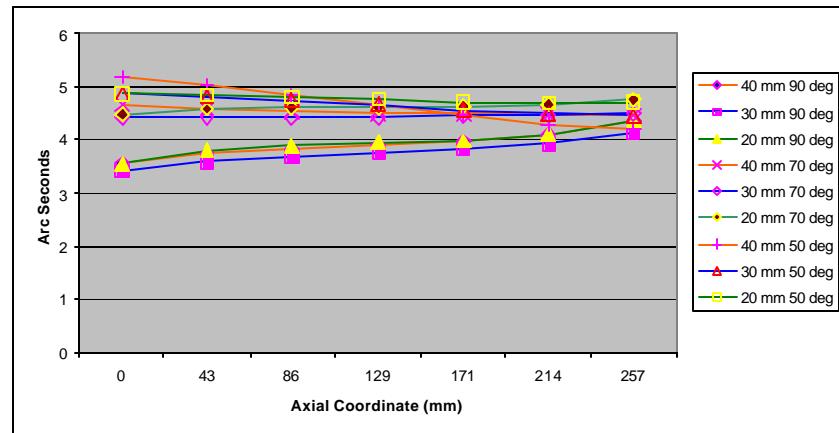
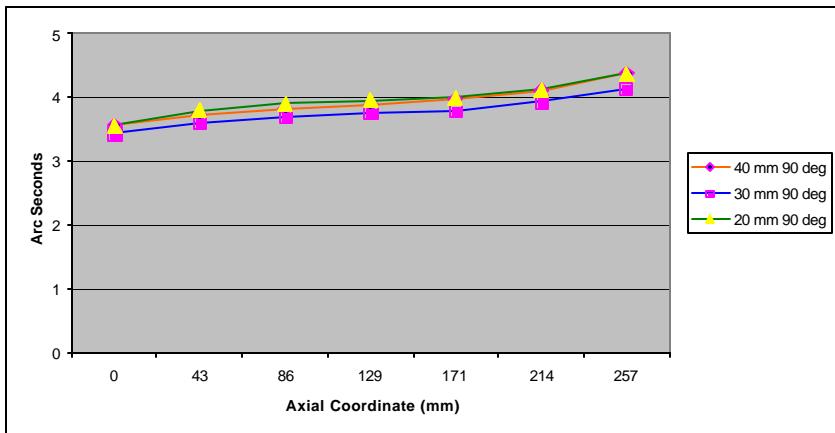
## Grav. Sag

**SWALES**  
AEROSPACE



**Warm Up @ 575 °C**  
**Prior to Glass Conforming to Mandrel**  
**Axial Direction Local Slope Change**

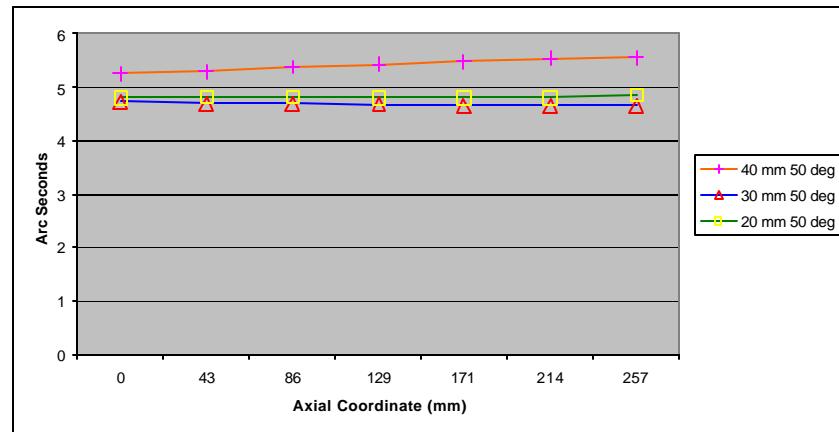
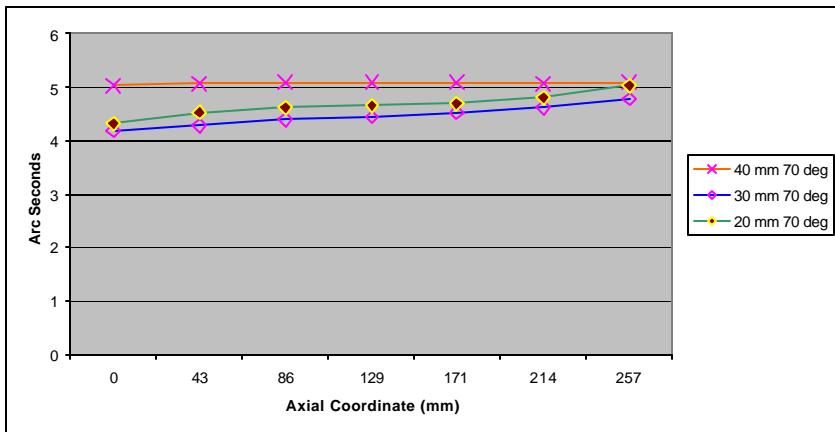
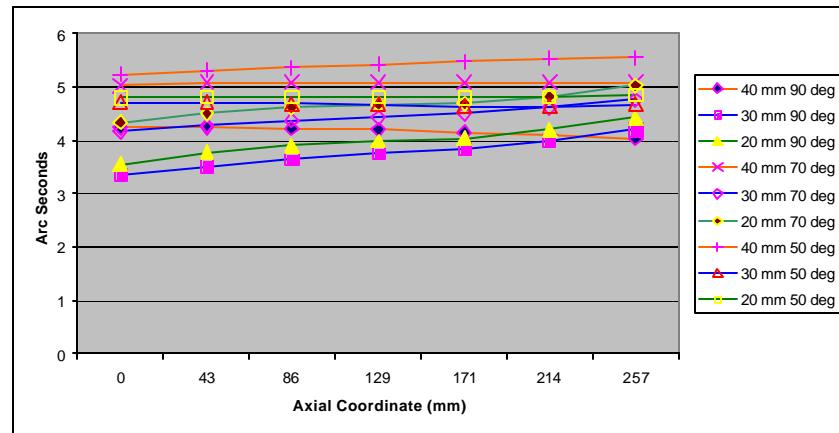
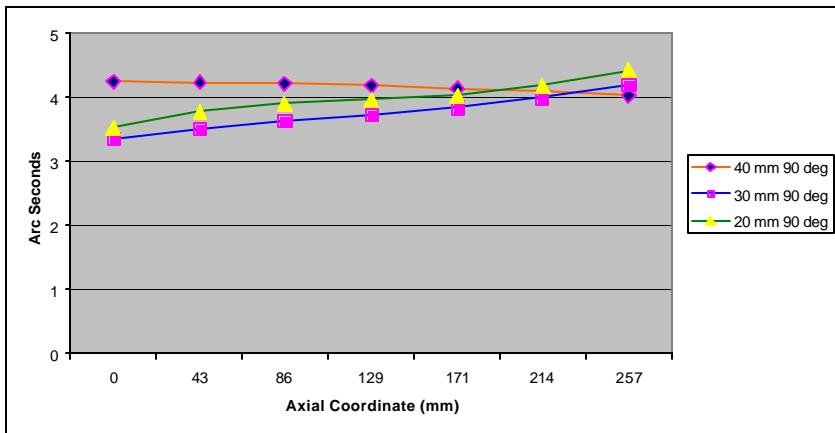
**SWALES**  
 AEROSPACE



Temperature Dependent Material Properties

# After Glass Conforming to Mandrel

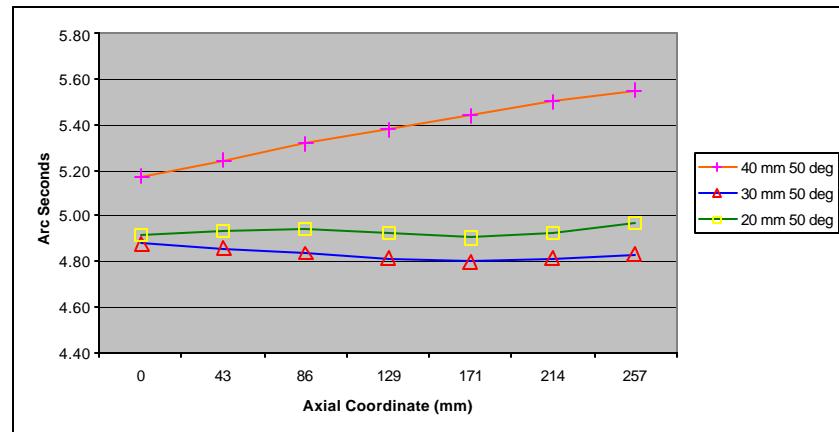
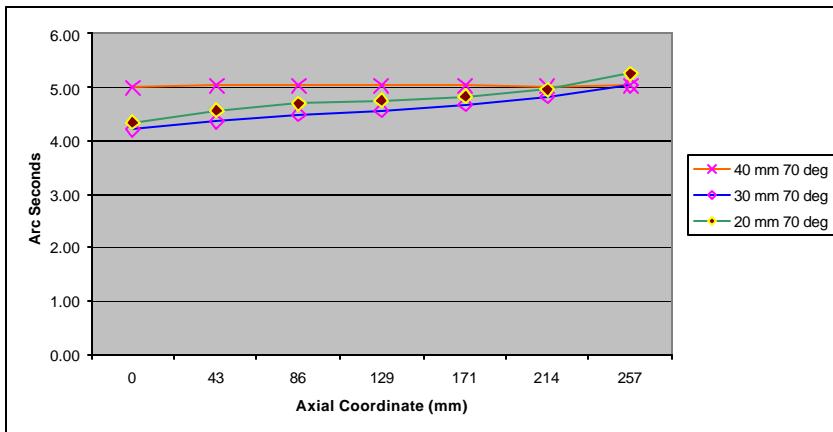
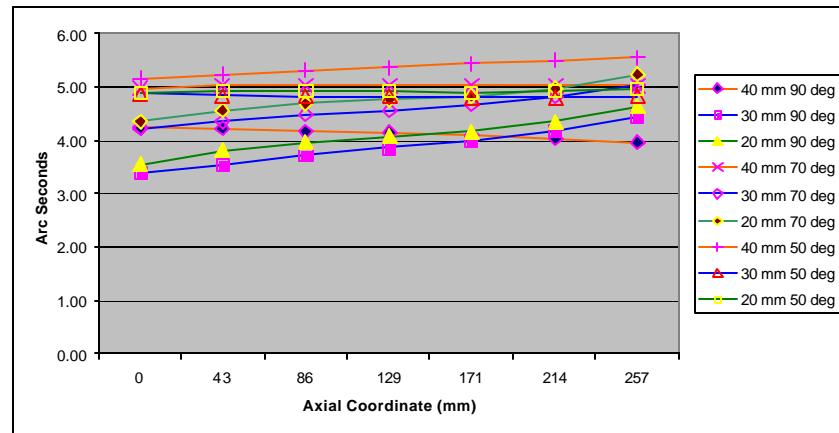
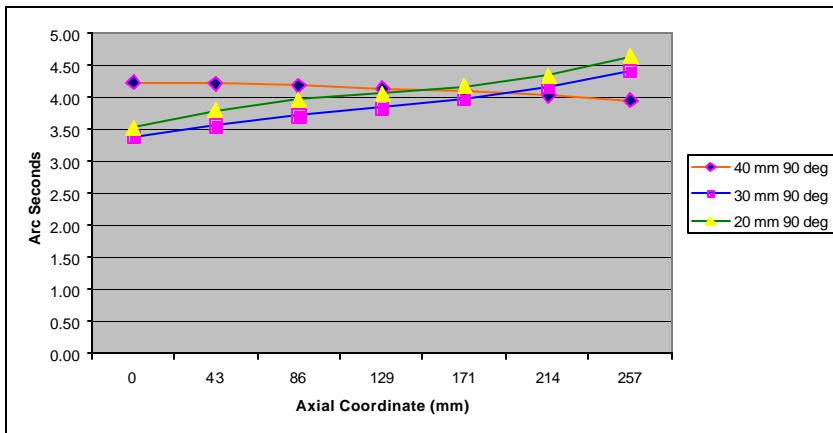
## Axial Direction Local Slope Change



Temperature Dependent Material Properties

# Soaking @ 615 °C

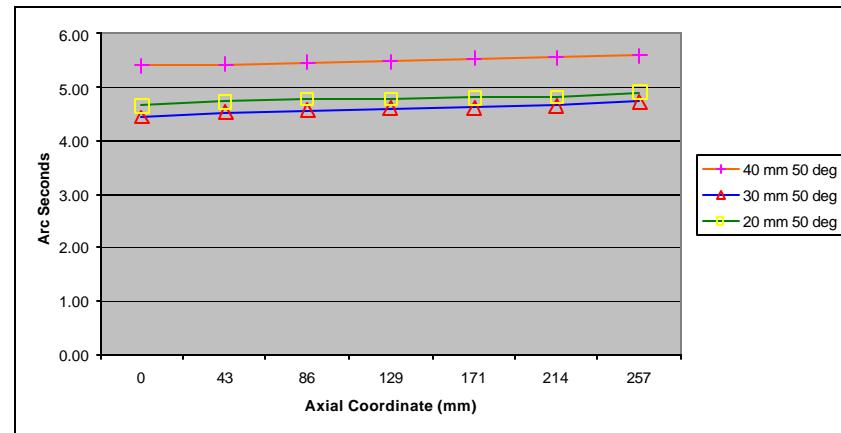
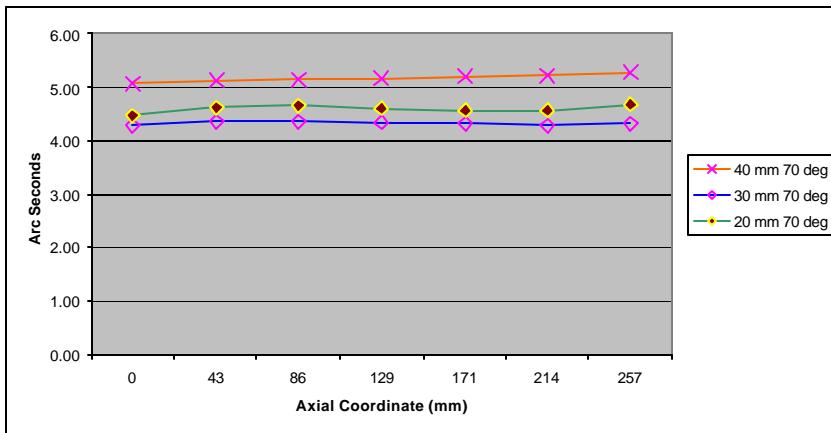
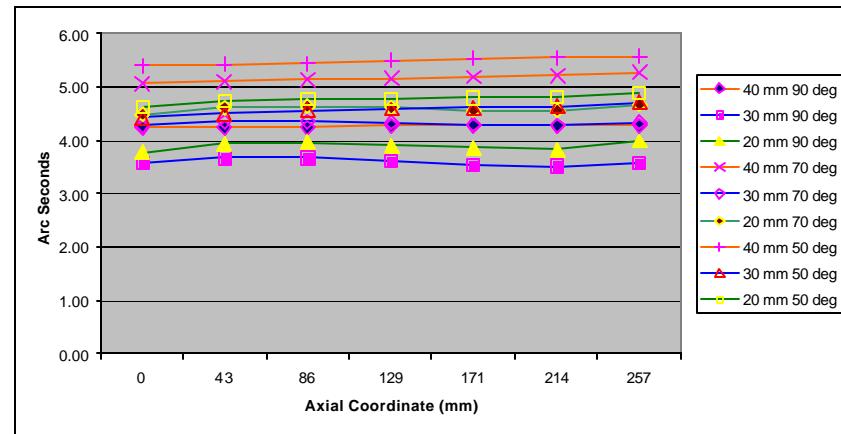
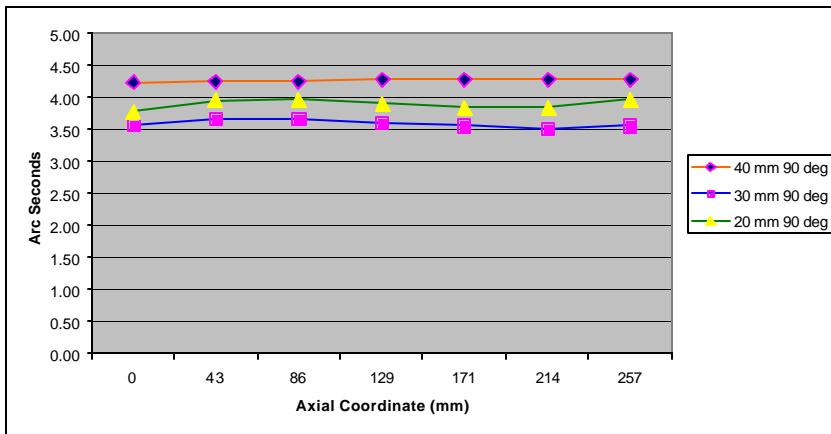
## Axial Direction Local Slope Change



Temperature Dependent Material Properties

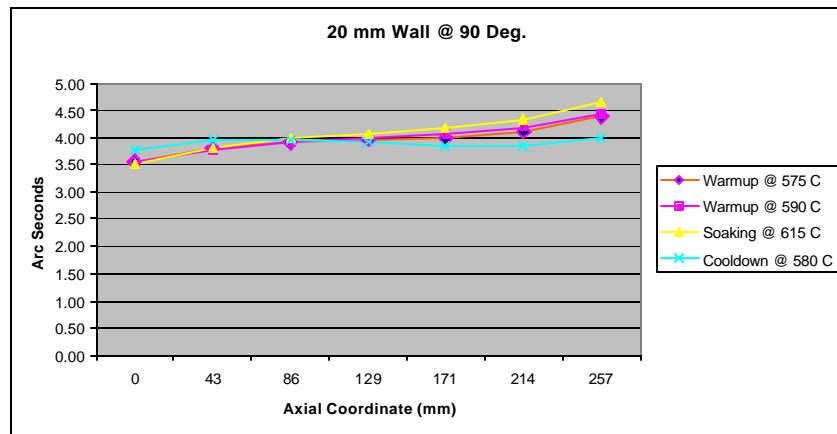
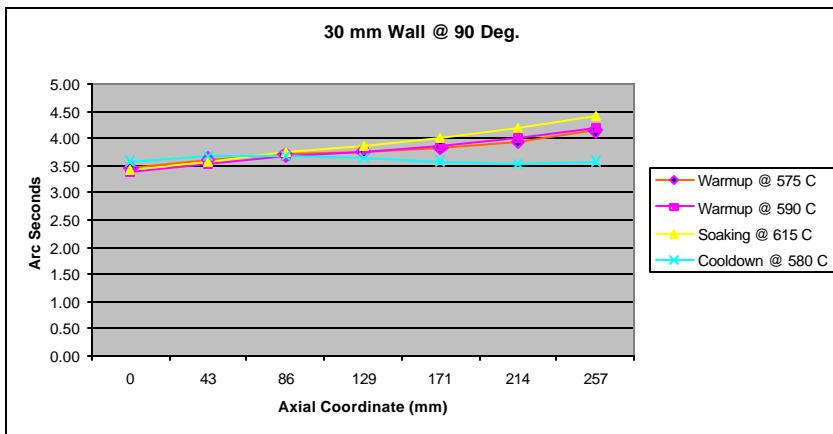
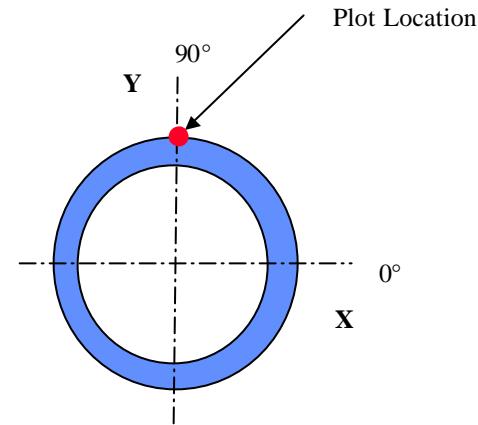
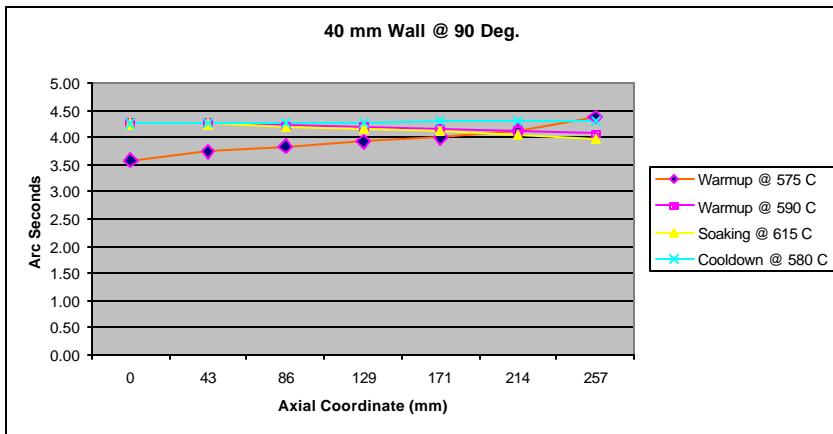
# Cool Down @ 580 °C

## Axial Direction Local Slope Change



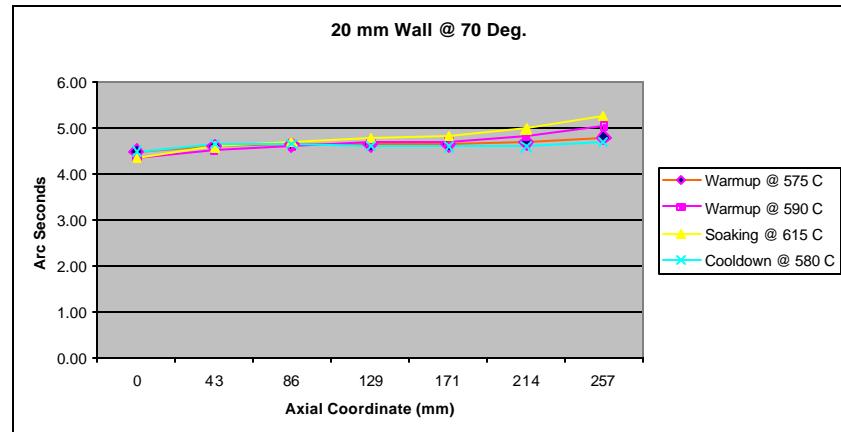
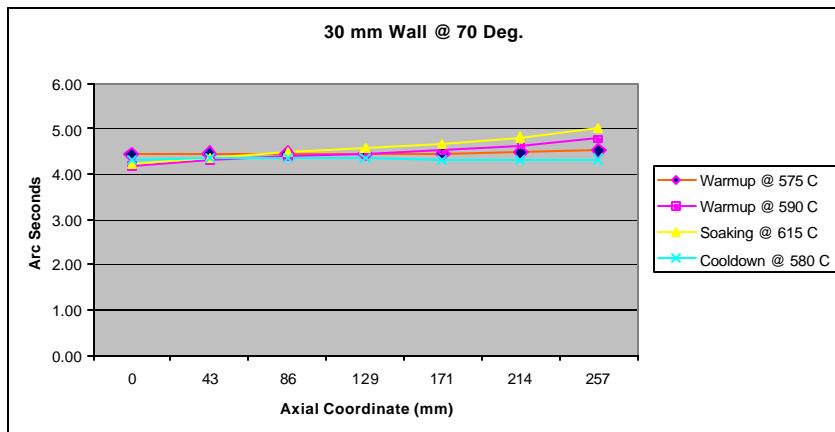
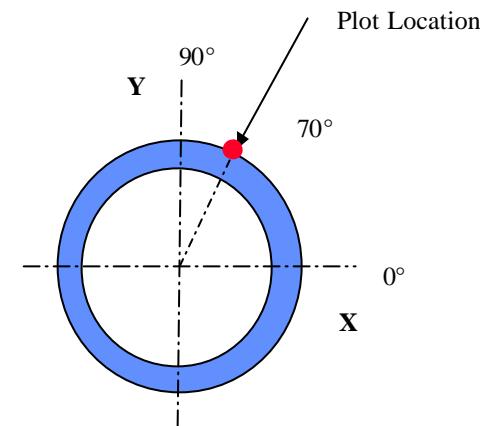
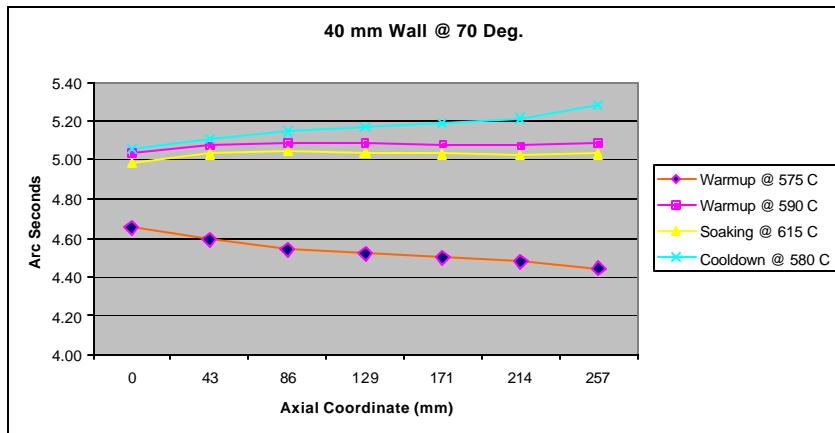
Temperature Dependent Material Properties

# Axial Direction Local Slope Changes At Various Thermal Profiles



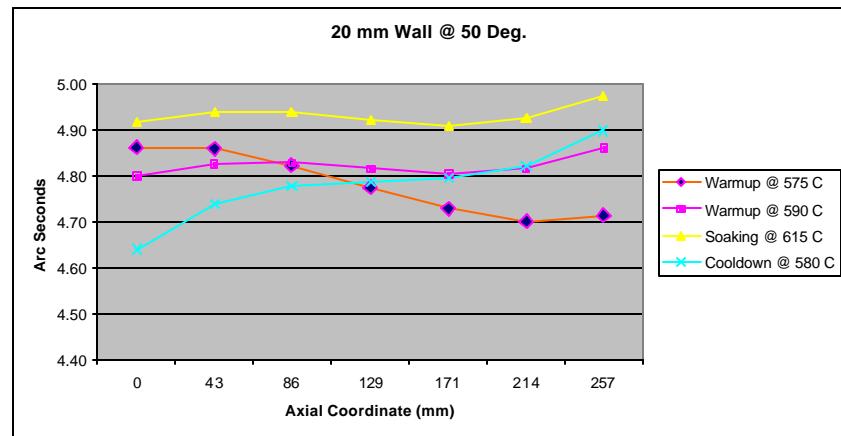
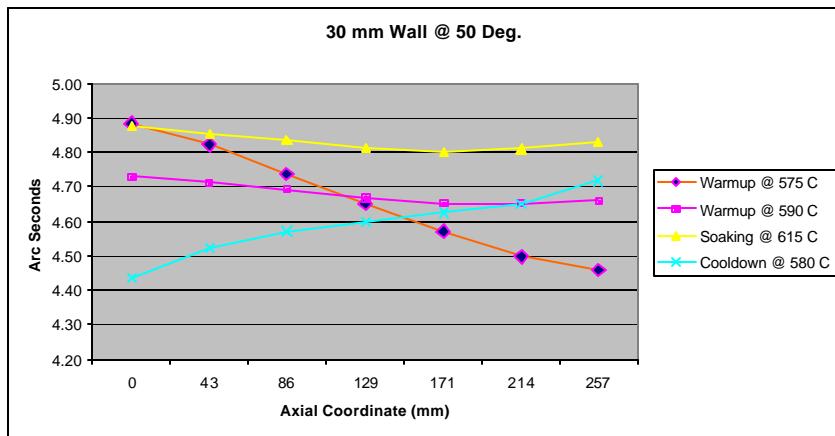
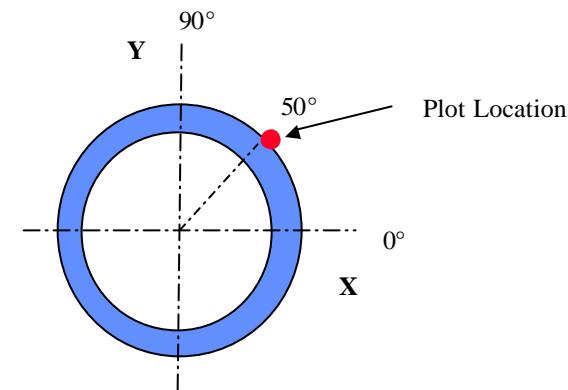
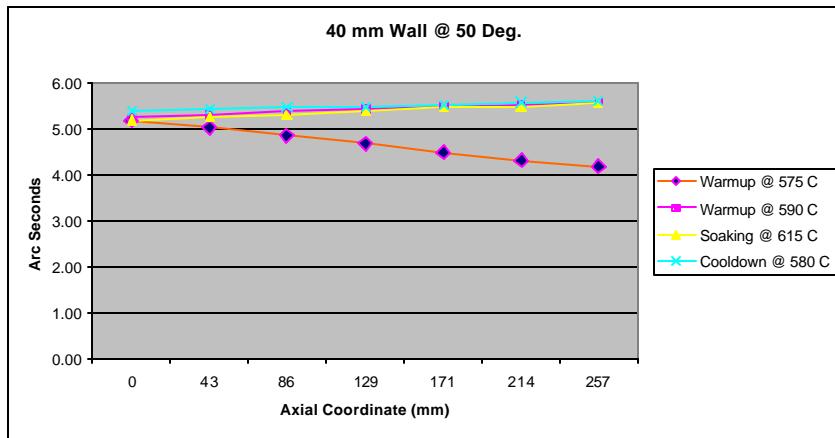
Temperature Dependent Material Properties

# Axial Direction Local Slope Changes At Various Thermal Profiles



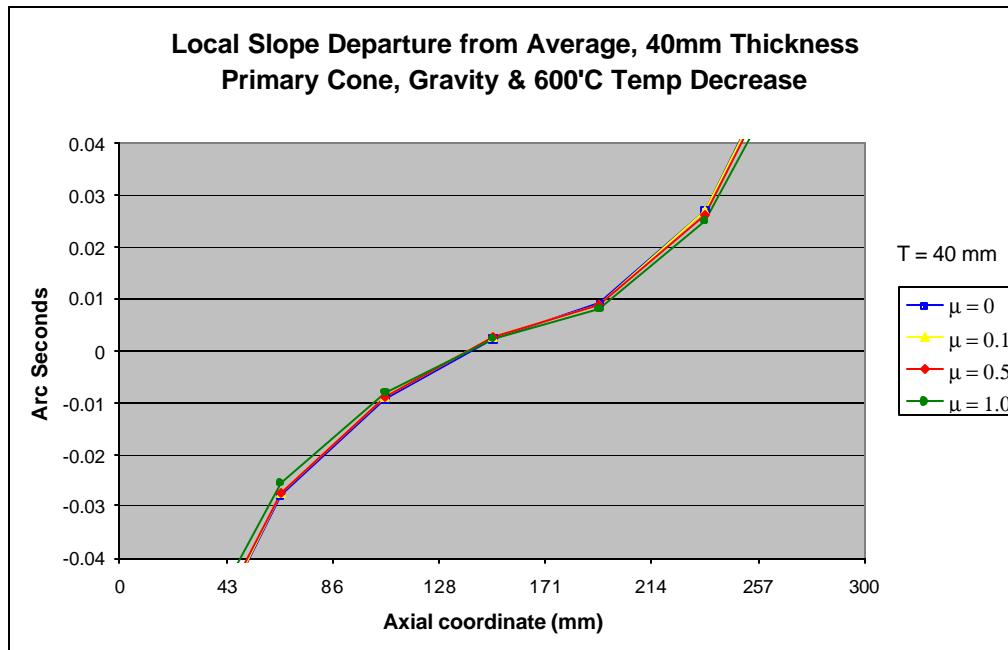
Temperature Dependent Material Properties

# Axial Direction Local Slope Changes At Various Thermal Profiles



Temperature Dependent Material Properties

# Effects of Coefficients of Friction

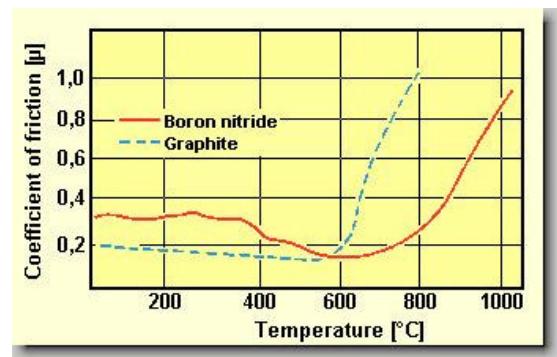


Left:

Effect of various Coefficients of friction produced insignificant variation as shown on the left

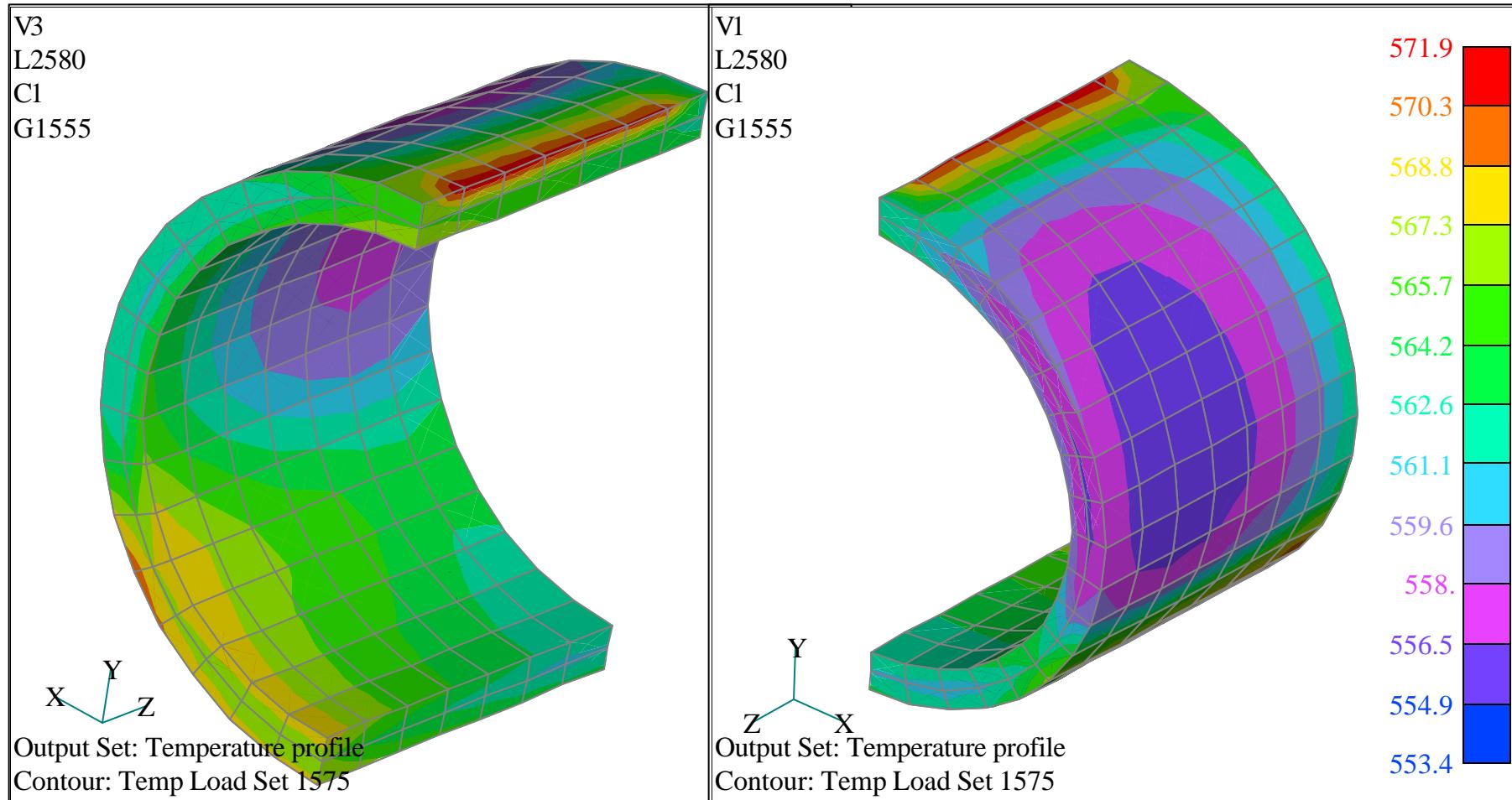
Below:

Coeff. Of friction for Boron Nitride

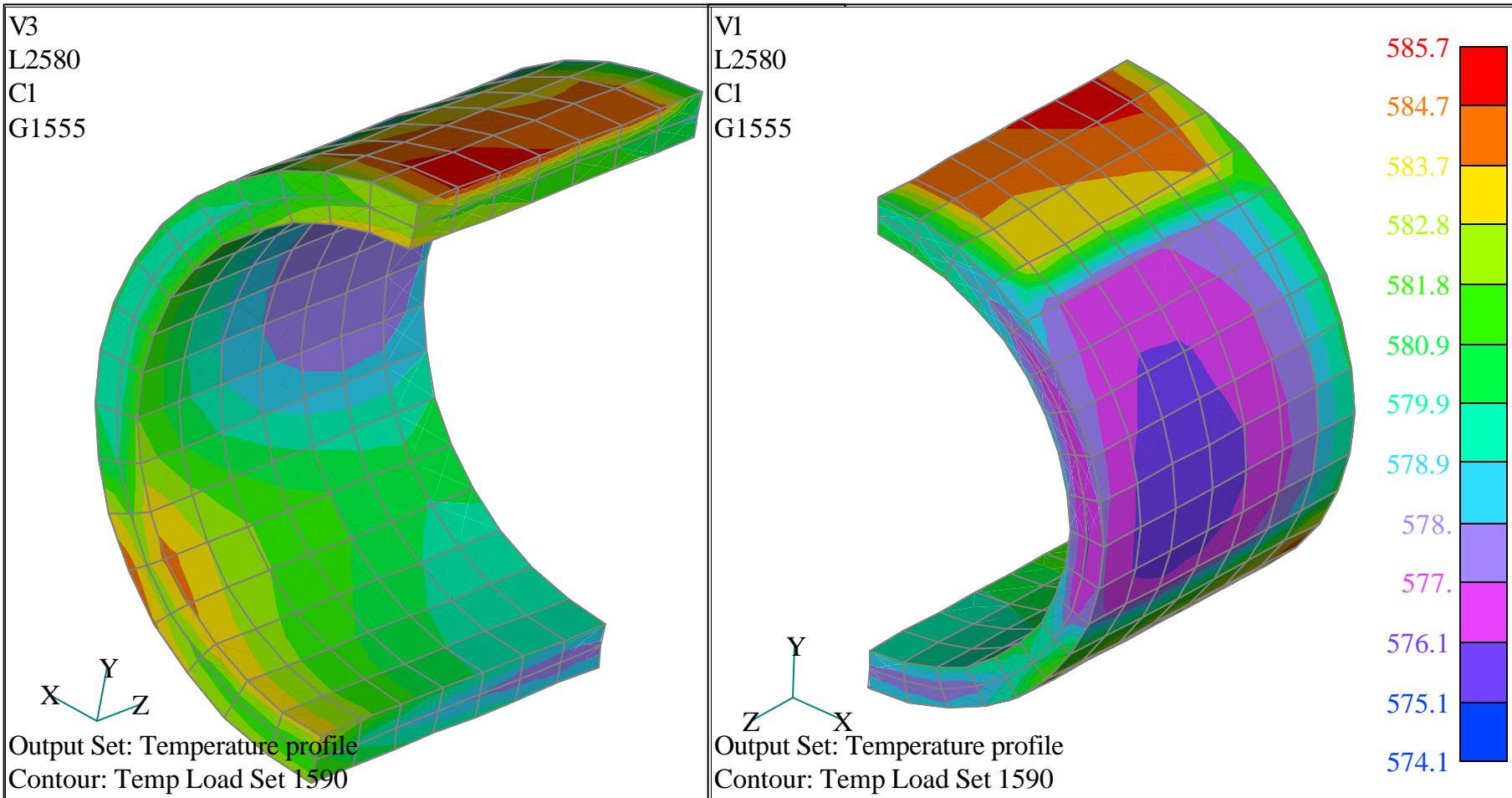


Büro für angewandte Mineralogie (Office of Applied Mineralogy)  
<http://www.a-m.de/englisch/literatur/ic0593-bild3.htm>

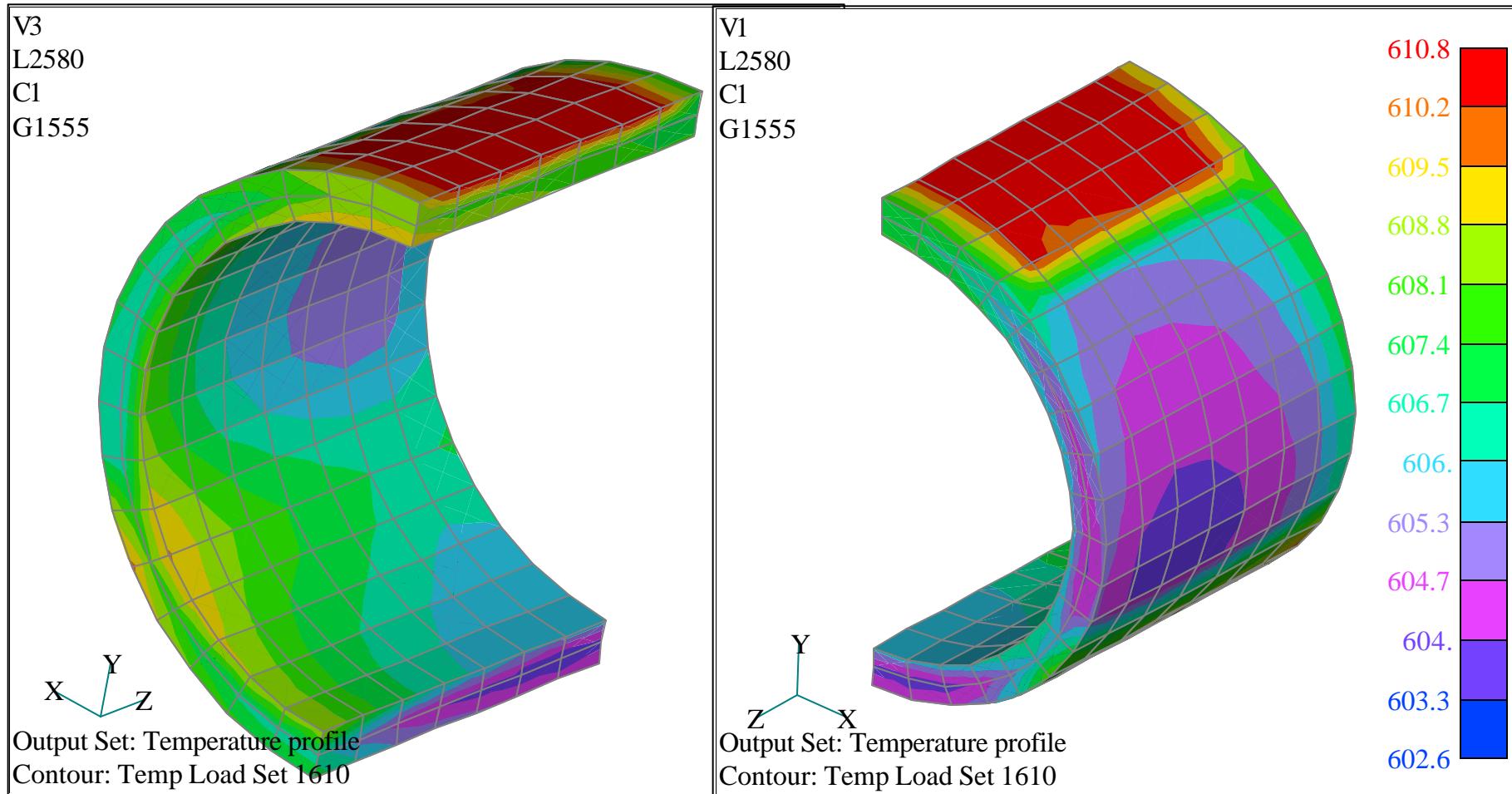
**Wall = 40 mm**  
**Warm-up @ 575 °C**



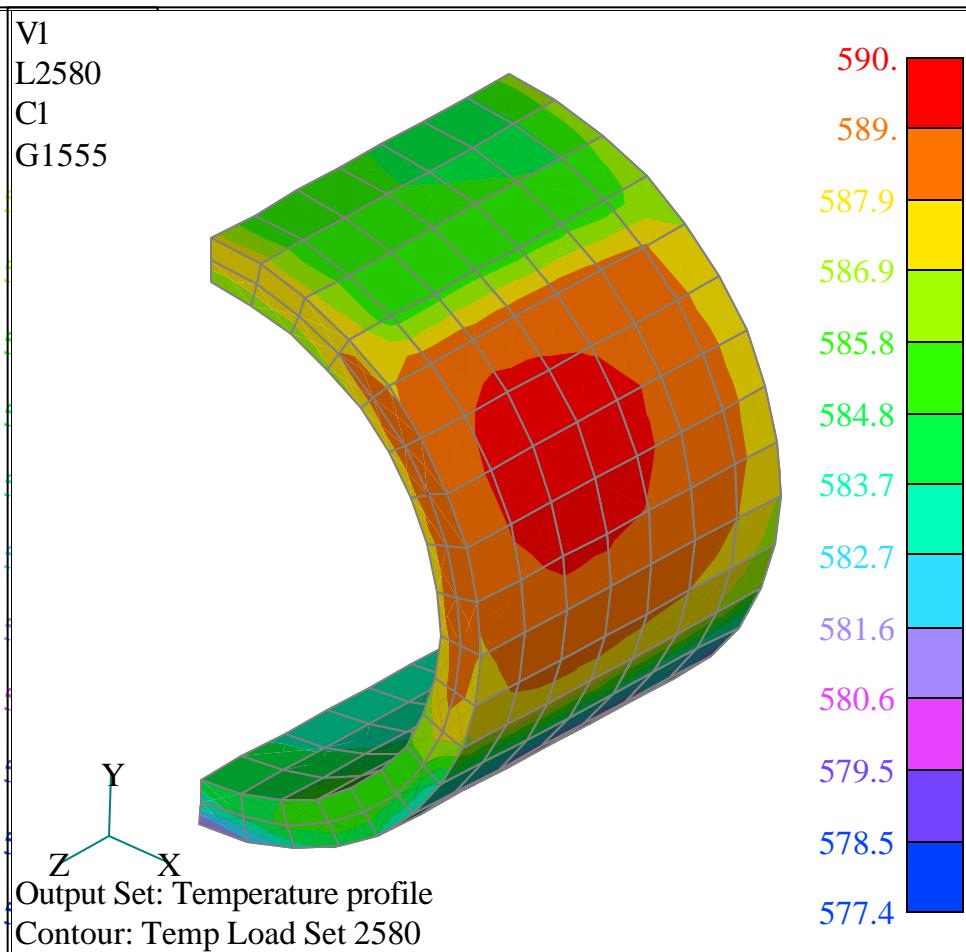
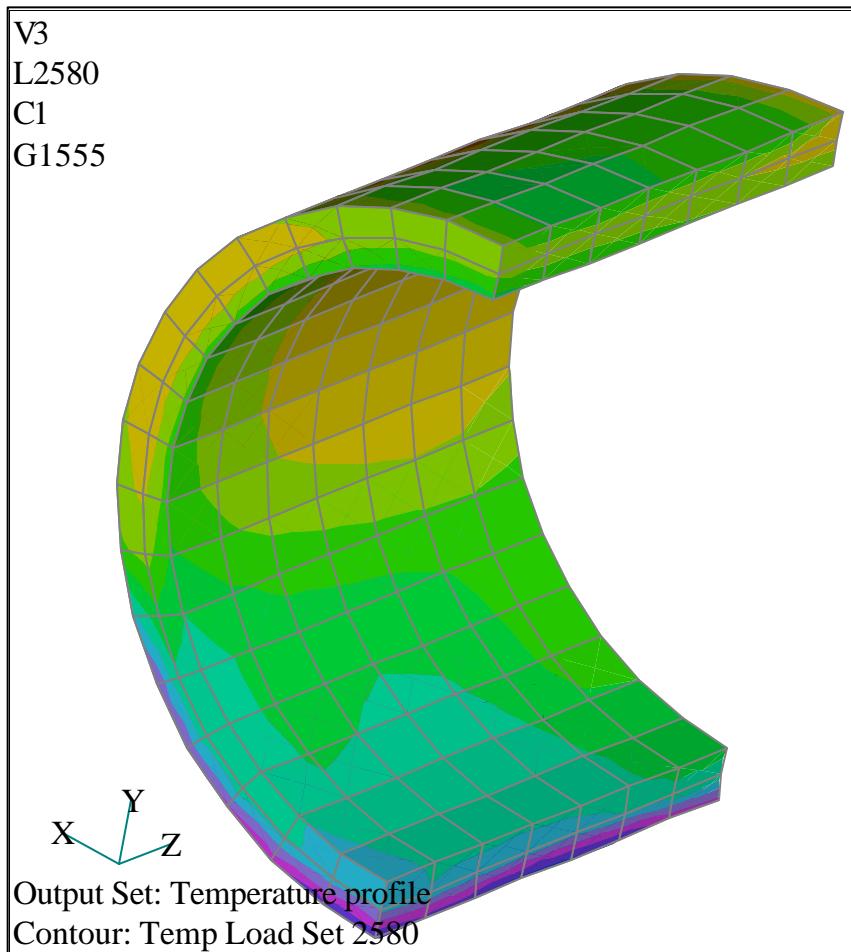
**Wall = 40 mm**  
**Warm-up @ 590 °C**



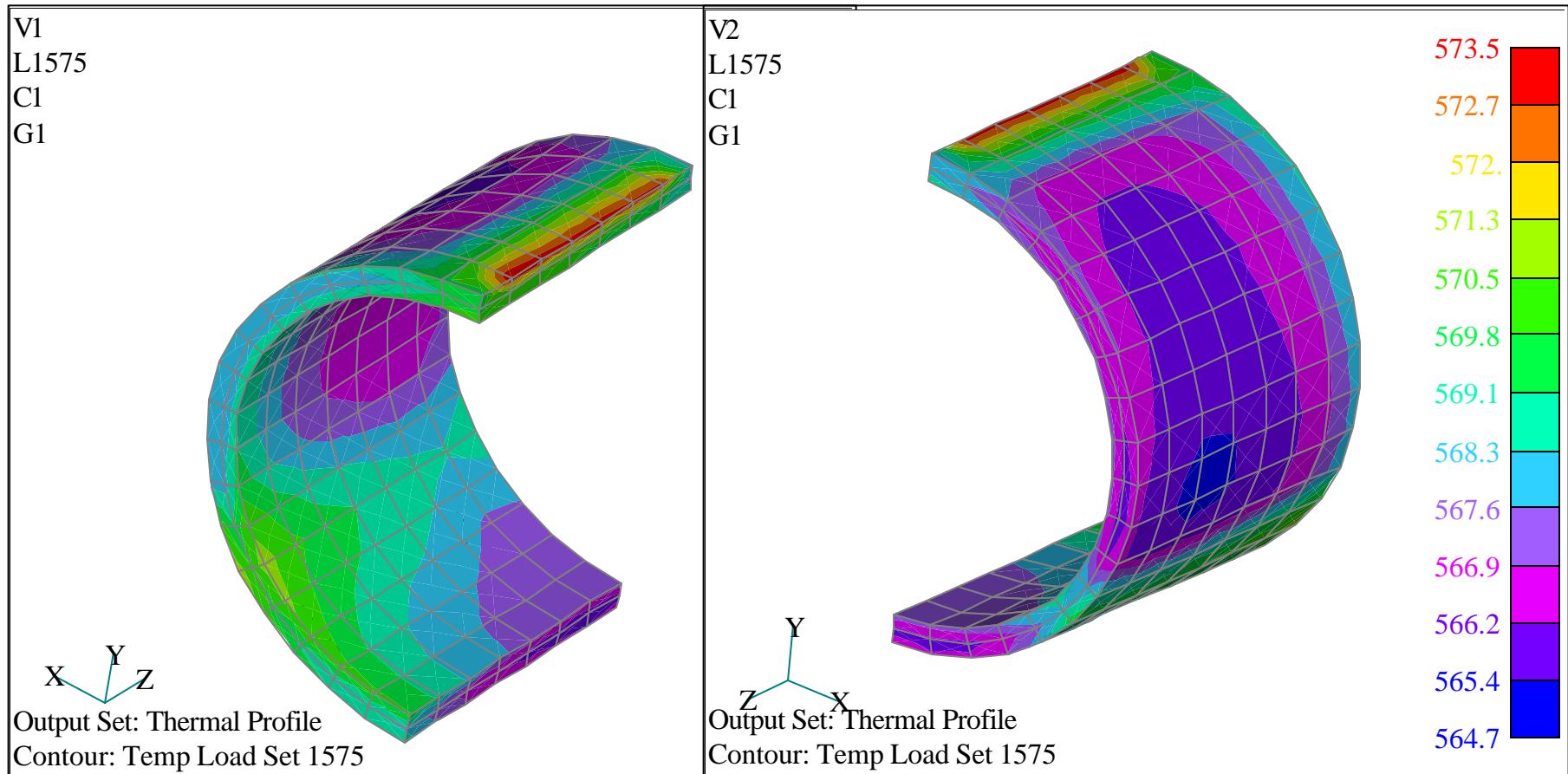
**Wall = 40 mm**  
**Soaking @ 615°C**



**Wall = 40 mm**  
**Cool-Down @ 580°C**

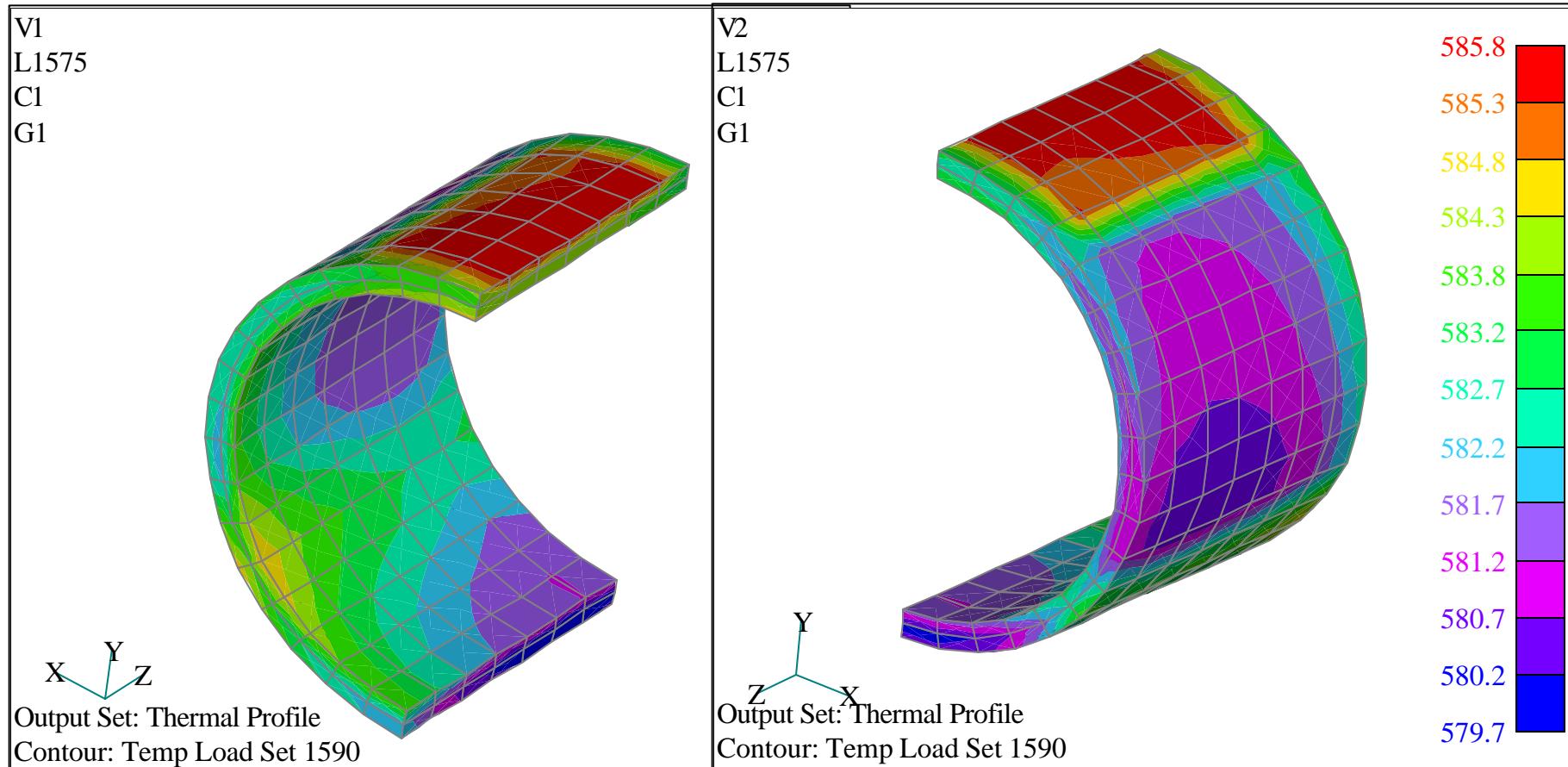


**Wall = 30 mm**  
**Warm-up @ 575 °C**



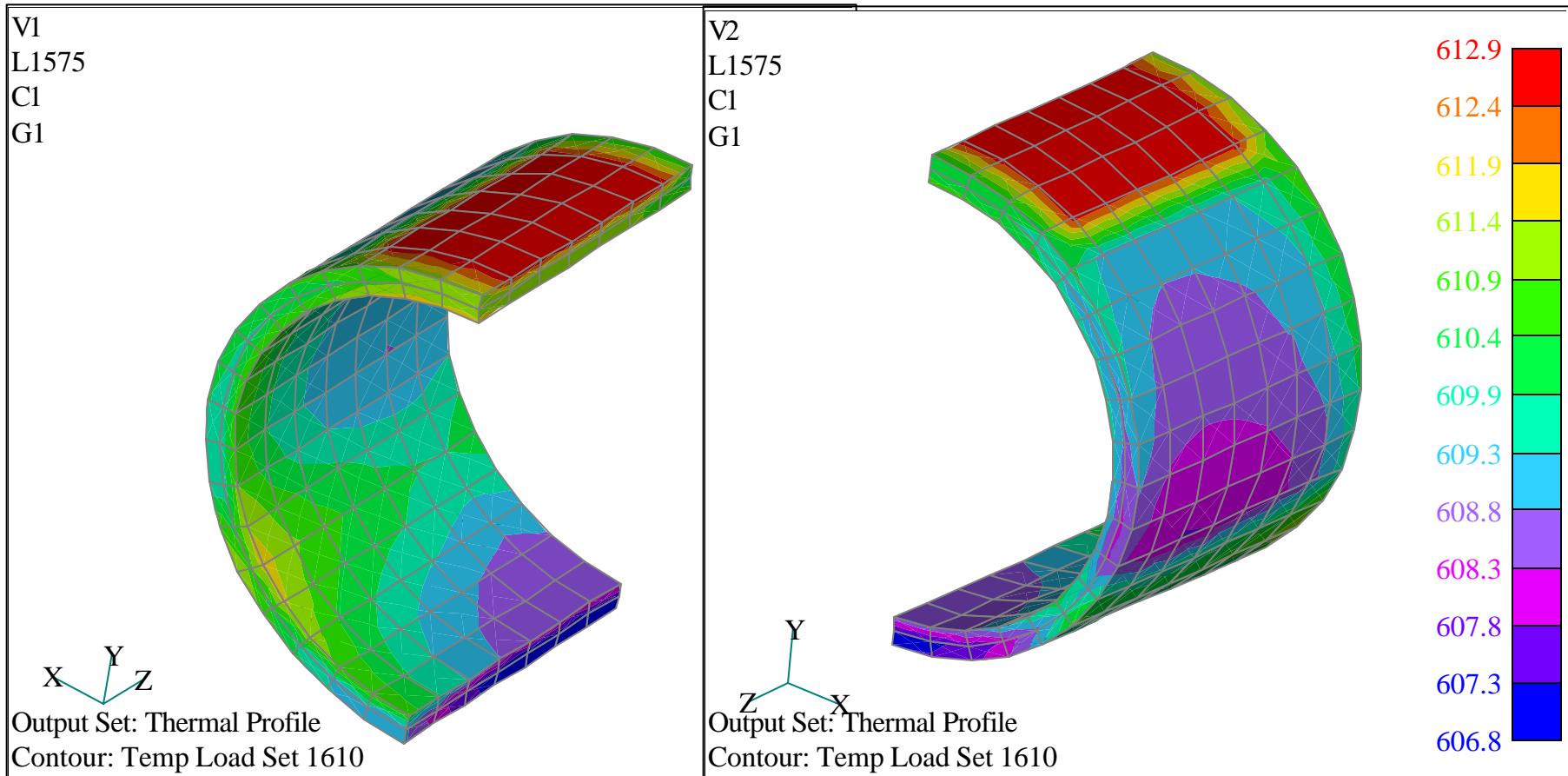
**Wall = 30 mm**  
**Warm-up @ 590 °C**

**SWALES**  
AEROSPACE



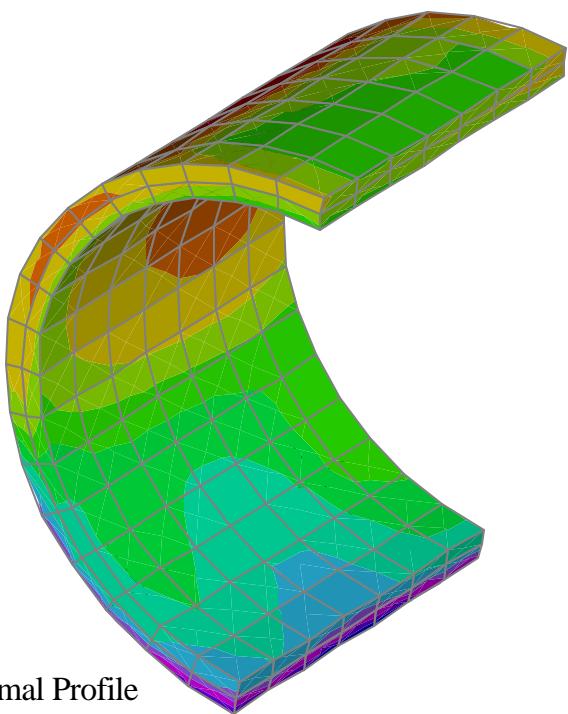
# Wall = 30 mm Soaking @ 615°C

**SWALES**  
AEROSPACE



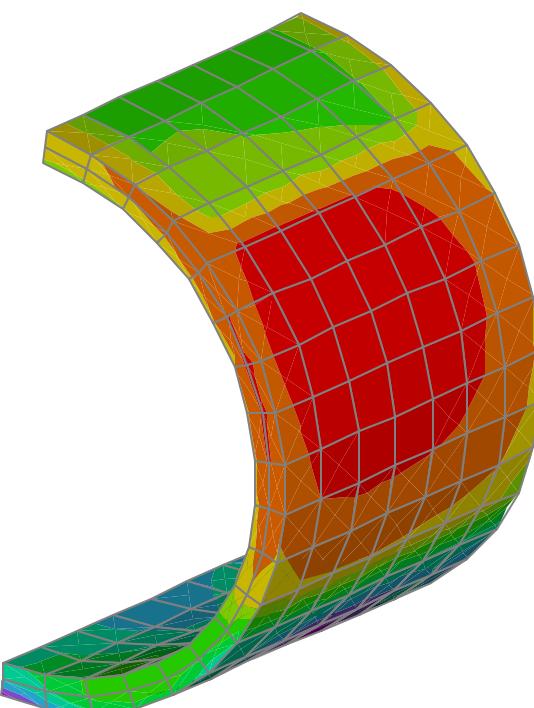
**Wall = 30 mm**  
**Cool-Down @ 580°C**

V1  
L1575  
C1  
G1

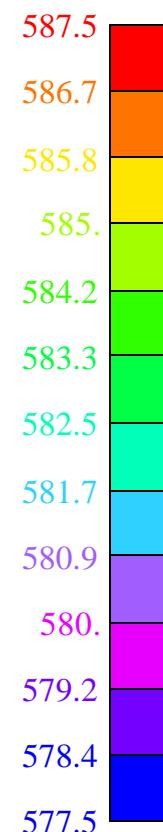


Output Set: Thermal Profile  
Contour: Temp Load Set 2580

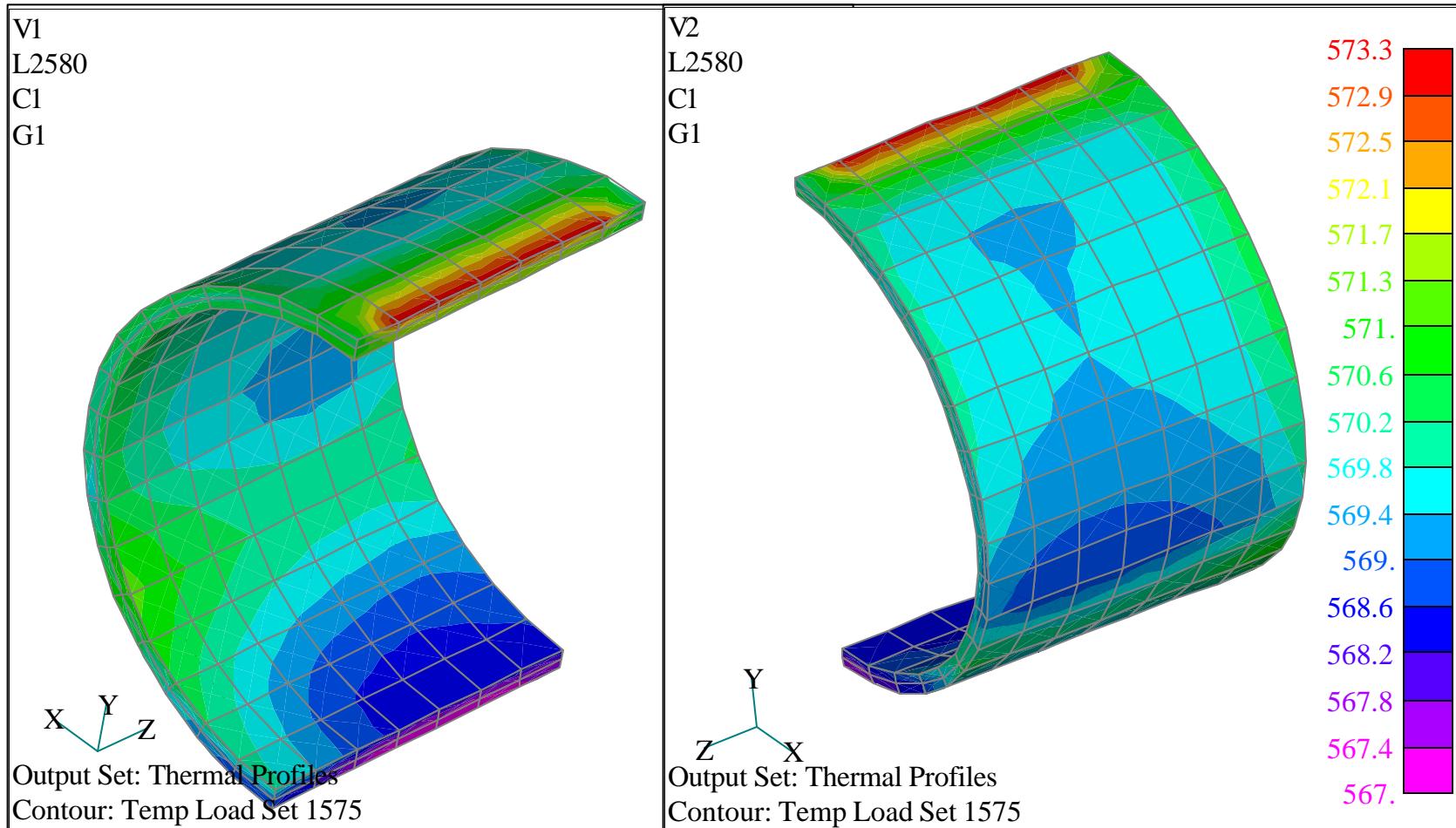
V2  
L1575  
C1  
G1



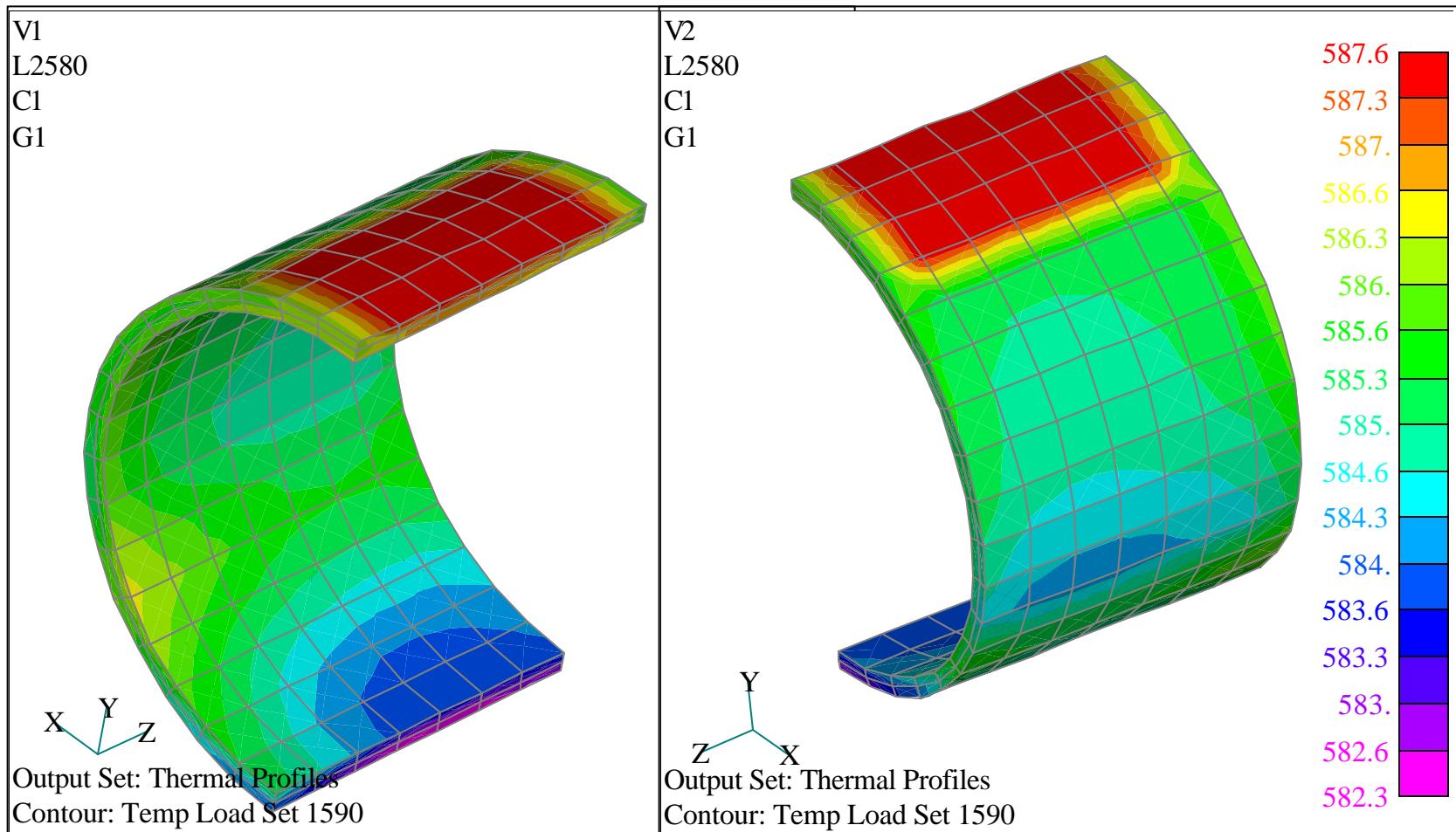
Output Set: Thermal Profile  
Contour: Temp Load Set 2580



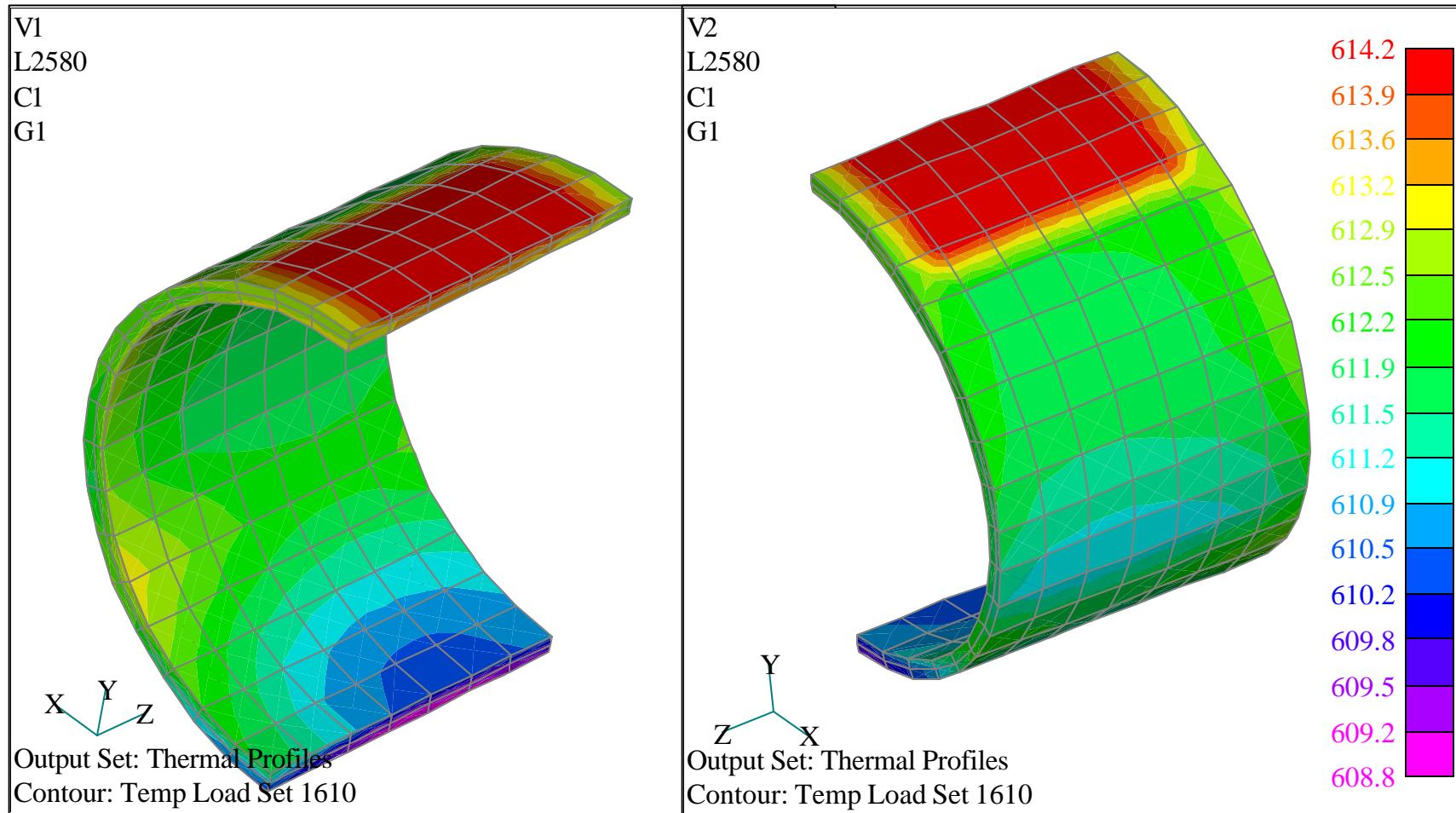
**Wall = 20 mm**  
**Warm-up @ 575 °C**



**Wall = 20 mm**  
**Warm-up @ 590 °C**



# Wall = 20 mm Soaking @ 615°C



# Wall = 20 mm

## Cool-Down @ 580°C

